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Perspective based scenarios

Analysis of a-priori sensitivity of water demand and the hydrological system to global change (Deliverable A1.x)

Report

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Analysis of a-priori sensitivity of water demand and the hydrological system to global change (Deliverable A1.x)

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CLIENT:	Institute of Inland Management and Waste Water Treatment (RIZA) Rijkswaterstaat Arnhem
TITLE:	Perspective based scenarios Analysis of a-priori sensitivity of water demand and the hydrological system to global change

ABSTRACT:

Within the framework of the national research program third tranche (NOPII-3) the research project "Integrated water management strategies for the Rhine and Meuse basins in a changing environment" NOP project number 958273) is carried out. The objective of this project is to provide an integrated framework for decision making in inland water management in the Rhine and Meuse basins under uncertainty in governing processes. This report covers an a-priori sensitivity analysis of the water systems and the models to simulate the processes that take place in these systems. The results are used to (1) define the variables that have the strongest impact on estimated river discharges, lake levels, and ground water levels, and (2) draw conclusions on the limitations of the applicability of the various models, on the types of changes that can be analysed by the models (directly and indirectly), and on the possibilities to estimate the impact of changes in climate and land use by inter- or extrapolation of other model scenario runs.

REFERENCES:	NRP projectnumber 958273 RWS/RIZA contract RI-3002 WL projectnumber R3325

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Summary

Within the framework of the national research program third tranche (NOPII-3) the research project "Integrated water management strategies for the Rhine and Meuse basins in a changing environment" NOP project number 958273) is carried out. The objective of this project is to provide an integrated framework for decision making in inland water management in the Rhine and Meuse basins under uncertainty in governing processes. This report covers an a-priori sensitivity analysis of the water systems and the models to simulate the processes that take place in these systems.

First, the relevant hydrological settings of the relevant sub-systems, Rhine and Meuse basins, IJsselmeer area and the Netherlands terrestrial area are described. Next, the applied models are discussed. These models include RHINEFLOW-2, WINBOS, BekkenWin, HydraWin, NAGROM, MOZART and MONA. The sensitivity of the model computations for a limited number of single and combined changes in climate and land use parameters is quantified. Based on these results, conclusions are drawn on (1) the limitations of the applicability of the various models, (2) the types of changes that can be analysed by the models, and (3) the possibilities to estimate the impact of changes in climate and land use by inter- or extrapolation of reference scenario runs or using a linear combination of them.

The results of the various models indicate that the discharge regime of the Rhine is sensitive to variations in precipitation. The effect of changes in evapotranspiration is somewhat less. Temperature changes have the smallest impact. Lake levels at the IJsselmeer are mostly affected by changes in sea level rise, followed by changes in discharge of the river IJssel. Changes in wind speed cause changes in water level near the boarders of the lake (wind set-up). Depending on the exact location this effect may become large. With respect to the terrestrial areas it was found that changes in precipitation and land use exceed the effect of changes in evaporation and transpiration. Also, areas were surface water levels are not regulated, such as the cover sand areas, have a stronger response to changes in precipitation than areas in which water levels are regulated, such as in polders.

Based on the model outcomes it also was concluded that the models can be applied to estimate changes in discharge, lake level, or groundwaterlevel as long as the expected changes in climate fall within the present range of temperature and precipitation variations. As most models do not have a linear response to the imposed changes in climate variables, it will be necessary to evaluate nearly all scenarios individually using the appropriate models.

1 Introduction

Within the framework of the national research program third tranche (NOPII-3) the research project "Integrated water management strategies for the Rhine and Meuse basins in a changing environment" NOP project number 958273) is carried out. The objective of this project is to provide an integrated framework for decision making in inland water management in the Rhine and Meuse basins under uncertainty. This uncertainty results from a number of unknown or partly known processes at different scale levels: global, European, national and river basin. These processes include on the one hand socio-economic and agro-economic developments (such as population growth, industrial expansion, land use changes, and use of different crop types), resulting in changes in the conditions of the water systems and which will affect water *demand*. On the other hand, changes in climate conditions and the inherent hydrologic response may affect water *availability*. These uncertainties determine possible futures that are envisaged, and can be coloured according to different perspectives people may have. Depending on the future perspectives different water management strategies may be adopted to solve future problems.

The project is subdivided into three phases. In the first phase, an a-priori sensitivity analysis of the water systems and the models to simulate them is carried out, and Perspective-based scenarios for future changes in climate and socio-economic developments are established. In the second phase, the scenarios will be calculated using the models. The evaluation of the scenario results and recommendations for the identification of robust scenarios under uncertainty will be carried out in the third phase. The present report is part of phase 1.

Contractnumber

WL | Delft Hydraulics functions as sub-contractor under RWS-RIZA. The project is financed by the NRP. The work is carried out under contract number RI-3002, sent February 22, 2000. The role of WL | Delft Hydraulics is described in the appendix of this contract.

Overview reports of the first phase of the project

Phase A

Sub-project	Activity	Report
A1	Analysis of a-priori sensitivity of water demand and the hydrological system to global change	Kwadijk et al. (2000), Analysis of a-priori sensitivity of water demand and the hydrological system to global change. Delft: WL|Delft Hydraulics.
A2	Description of climate change scenarios	In progress - KNMI
A5	Theory of Perspectives method and establishment of scenarios (ICIS)	PhD-Thesis Van Asselt, summary is in progress.
A7	Discussion of the scenarios with policy makers and stakeholders in a workshop.	Van Asselt, M. & N. Van Gemert (2000), Toekomsten voor Rijn en Maas. Verslag Stakeholder workshop. Maastricht: ICIS.
A	Final report Phase A: Description of the Perspective based scenarios.	In progress - ICIS

1.2 Rationale

An a priori sensitivity study was scheduled for the following reasons:

- We expect that the scenarios that will be defined in the next phases could be (far) outside the range for which the models of the physical system were tested during the earlier research projects NOP I and NOP II. We believe that it was necessary to give an indication of the limits to which the models can be used with acceptable reliability. In this respect we also paid attention to combined climate and/or land use changes that could lead to unexpected (and unreliable) large model responses.
- Contrary to the way future scenarios were used during NOP I and NOP II, the scenarios that will be defined in the next phases will not only include climate and land use changes but also changes in measures and water management styles. We think that it is necessary to explore the capability of the models to simulate such changes.
- We also expect that the following phases could result in a huge number of different scenarios. To decrease the computing effort, we therefore explored the possibilities of estimating changes from interpolation between reference scenarios (e.g. the hydrologic response on a 4 degrees temperature rise could be two times the response on a 2 degrees temperature rise). We also investigated whether the effect of combinations of changes in different input variables (e.g. precipitation and evapotranspiration) can be estimated as a linear combination of individual results obtained for changes in one single variable. This is particularly important to analyse whether it is possible to derive the response from changes that will have opposite effects.

1.3 Scenario definition

To execute the sensitivity analysis the following types of changes were explored:

- Changes in climate variables such as temperature, precipitation evaporation and sea level separately.
- Combined changes in temperature, precipitation, evaporation and sea level rise.
- Changes in land use.
- Changes land subsidence
- Changes in water use efficiency of crops.
- Combined changes in climate variables and land use and/or water use efficiency.

We did not analyse all model parameters separately, neither were all scenarios executed with all models. With respect to the first, some models, e.g. the IJsselmeer models, use a large number of parameters, some of them directly representing climate (e.g. evaporation) or indirectly representing climate (e.g. discharge of the river IJssel), others represent different management styles (e.g. pumping capacity). It is too much effort to explore the sensitivities separately. For these models we therefore used combined scenarios, envisaging relative extreme changes. With respect to the second, some models are not sensitive at all for certain changes (e.g. the RHINEFLOW model for a sea level rise). This means that it has no use to run such scenarios with these models.

The basin models were analysed with separate changes in precipitation, temperature, evaporation and land use. Also combined changes were applied. Apart from the effect of sea level rise, the IJsselmeer models were analysed using combined changes, based on a GCM-experiment with the UKHI model. These changes are referred to as UKHI2020, UKHI2050 and UKHI2100 (Grabs et al., 1997). These changes were obtained by linear interpolation of the UKHI2100 change. In this report the scenarios are applied as scenarios for a sensitivity analysis rather than climate changes estimates for a given projection year. Hence, they can be regarded as scenarios in which changes in temperature are low, medium, or high. The applied changes in temperature and precipitation are given in table 1.1.

Table 1.1 Applied changes in temperature and precipitation for the sensitivity analysis, based on the UKHI2020, UKHI2050 and UKHI2100 estimates.

	Low	Medium	High
Annual avg. temperature	+ 1 °C	+ 2 °C	+ 4 °C
Total annual precipitation	+ 3%	+ 6%	+12%
Total summer pecipitation	+ 1%	+ 2%	+ 4%
Total winter precipitation	+ 6%	+12%	+25%

1.4 Set-up of the report

Using the results of previous studies (including the previous NRP project) and using the available modelling tools, a cause-effect chain analysis and an a-priori sensitivity analysis of the hydrological system and water demand to global change will be carried out. This will indicate which variables need to be defined in the scenarios. Also, it may reduce the number of variables needed to describe the hydrological changes.

For this purpose we first describe the relevant hydrological settings of the relevant sub-systems, Rhine and Meuse basins, IJsselmeer area and the Netherlands terrestrial area. We add a qualitative estimate of the main hydrological sensitivities to this description.
Secondly we describe the models used to estimate the sensitivities to global change and discuss the way the parameters and variables have to be changed in order to simulate various environmental changes such as climate and land use change.

Thirdly we report the quantitative sensitivity of different output variables of the models for a limited number of single and combined changes.

The final chapter summarises the results and recommends the way different global change issues should be simulated with the different models.

2 Description of the water system and a-priori estimate of the sensitivity to environmental change

2.1 Rhine and Meuse basins

2.1.1 Hydrological setting

The drainage basin of the river Rhine covers about 185.000 km² and stretches from the Swiss Alps to the river mouth in the North Sea. Two thirds of the basin are located in the Federal Republic of Germany. The Alpine countries, Switzerland, Austria, and Lichtenstein, form 20% op the total area. Other areas that are part of the drainage basin are France, Luxembourg, Belgium and the Netherlands.
At Basel, where the River Rhine leaves Switzerland, the river has a typical snow melt driven regime, with high discharges in summer and relatively low flows during the winter period. The hydrological response of the Alpine basin section is largely determined by the existing lakes that damp the flash floods from the mountains. Flowing to the North the regime becomes more and more dominated by the annual course of precipitation and evapotranspiration. Under the current conditions the River Rhine at the German-Dutch border has a combined rainfall-snow melt driven river regime. This means that discharge is relatively equally distributed over the year. The winter season shows the largest discharges originating from precipitation in the German and French parts of the basin. Summer discharge originates mainly from melting snow in the Swiss Alps when evaporation surpasses precipitation in the lower regions.

The basin of the River Meuse covers an area of approximately 33,000 km². The Meuse is entirely rain-fed, usually showing high discharges in winter and very low discharges in the summer period. Although the character of the river is entirely rain-fed, there are differences in river behaviour within the basin. These differences are mainly due to spatial differences in the amount of precipitation, geomorphology and geology of the sub-surface. The upper part of the basin, located in France is long and narrow, with small gradients. The valley sides are gentle. The river flows through alluvial deposits underlain by calcareous rocks. In its central section the river Meuse has cut its way through the Ardennes in Belgium. Gradients here are steeper than in the upper section. The valley sides are steep upward, leading to an undulating landscape. Due to the steeper gradients, flow velocities are high resulting in small travel times in both the main river and the tributaries.

2.1.2 Qualitative estimation of the hydrological sensitivity to environmental change

The river Rhine

Temperature change, runoff and water availability
Temperature change in the Rhine basin will lead to an upward shift of the snow line in the Alpine basin section. Without any other changes this will lead to higher discharges in winter and lower discharges in the spring and summer period. In the Alpine sub-basin this will lead to less water availability in spring and summer.

In the downstream sections the effects of reduced snow cover will only be present in the runoff of the main river as here snow melt is not a significant part of the runoff. Temperature change will also increase evaporation. In the whole basin this will lead to a reduction in water availability and runoff in summer. Temperature change will therefore probably lead to higher average discharges in winter in the entire basin and lower in summer.

Temperature effects on peak floods and low flows
In the Alpine basins temperature change alone may also shift peak flows from the summer to the winter period. Effects of temperature change on peak flows in the downstream section are discussed by Kwadijk and Middelkoop (1994). They suggested that the effects of temperature changes were relatively small and stated that peak flows in the river Rhine were more sensitive to precipitation than to temperature changes.
Temperature rise will lead to a reduction of discharge in summer due to increasing evaporation. This also means that dry spells will increase. The effect will be largest in the sub-basin downstream of Basel as here already the evaporation exceeds the precipitation in summer.

Precipitation effects on runoff and water availability
Effects of precipitation change to runoff are straightforward. Increasing precipitation obviously will result into increasing discharges. In the winter period in the Alps precipitation change only will result in relatively small changes in discharge as in the largest part of the area precipitation will fall in form of snow. In the downstream section the effect of increasing precipitation will be greatest in the winter period. Large parts of the precipitation surplus will come to discharge, as runoff coefficients in winter in this sub-basin are already high. Water availability will follow the change in precipitation.

Precipitation effects on peak floods and low flows
Previous research (Kwadijk, 1993, Kwadijk and Middelkoop, 1994, Grabs et al., 1997) suggested that the discharge of the River Rhine was very sensitive to changes in precipitation. Precipitation increase only will lead to higher peakfloods in the Alps as both baseflow and direct runoff will increase in summer. Also in the lower reaches of the River Rhine peak flows will increase with increasing precipitation and decrease with precipitation reduction.

Combined effects of temperature and precipitation change
The same authors showed that the effect of temperature change in the basin is smaller than the effect of precipitation change. Climate scenarios assuming a combination of both a temperature rise in all seasons, a precipitation increase in winter and a reduction of rainfall in summer will lead to the most severe changes in both runoff and water availability in the downstream part of the basin. Average winter runoff will increase together with peak flows. Meanwhile summer discharges will decrease and frequency and intensity of dry spells will increase.

2.1.3 The river Meuse

Although the response of the Meuse catchment to isolated components of the climate change are unambiguous, the qualitative estimates of the sensitivity of the river Meuse to the combined components of climate change is more complex. Since the Meuse is not a snow-fed river, the effects of temperature change on runoff is not as pronounced as in the Rhine basin, but the effects of the other isolated components are similar to the effects described for the Rhine catchment. However, due to interrelated influence of these individual components the combined effects are not sufficiently analysed. Presently, a study is carried out (RIZA project RI-2988B) for a more detailed analysis. Results of this study will become available in October 2000.

2.2 IJsselmeer area

2.2.1 Hydrological setting

The IJsselmeer area contains the linked lakes IJsselmeer, Markermeer and Randmeren. The lakes are shallow with an average water depth of 4 meters. This freshwater inland lake is mainly fed by the IJssel branch of the river Rhine. In winter the surrounding polders drain their surplus water towards the lake. The lake itself drains mainly towards the Wadden Sea in the North and through the North-sea canal and the Amsterdam harbour into the North Sea. Water is also exchanged between the lake and the Amsterdam-Rhine Canal. In summer water from the lake is flushed to the polders and water evaporates from the lake.

The basis of the water management in the IJsselmeer area are decisions about so-called 'target' water levels, and agreements between water authorities. The lake target levels in the IJsselmeer and Markermeer are NAP -0.40 m (NAP = Dutch Ordnance Datum) in winter. This low level is to achieve a sufficiently large storage capacity for excessive water from the IJssel during periods of high river discharge, and from the surrounding polder areas, without risking too high water levels. During summer, the target level is NAP -0.20 m. This higher level is maintained to enable a larger amount of fresh water stored in the lake to fulfil the high water demands from the surrounding land during periods of a net precipitation shortage. The discharge into the surrounding area occurs generally by gravity. Therefore the level in the IJsselmeer area has to be higher than in the surrounding area.

Further a minimal head loss is necessary in order to get enough capacity. Since extremely high lake levels (e.g. due to peak flows of the IJssel River) do not occur during summer, this higher level has no adverse effects on safety. The target levels in the border lakes are slightly higher than in the IJsselmeer. In the summer season the lake target levels can be easily maintained. During winter, however, the lake levels are systematically higher than the target level. This is because at target level the discharge capacity of the sluices in the Afsluitdijk is lower than the average total discharge into the lake. Particularly unfavourable weather conditions, mainly the wind speed and direction, and fluctuations in the river IJssel discharge cause lake levels exceeding the target levels. Because the other lakes discharge their water into the IJsselmeer, their lake levels are influenced by the level in the IJsselmeer. The target level in Amsterdam-Rijnkanaal/Noordzeekanaal is at NAP -0.40 m throughout the year. In practice this is a mean value. The water level normally fluctuates between NAP -0.5 m. and -0.3 m.

The ease of maintenance of these levels thus strongly depends on sea level and wind, as the IJsselmeer drains by gravity into the Wadden Sea. Water quality in the lake mainly depends on the quality of the River Rhine water and on the residence time of the water in the lake.

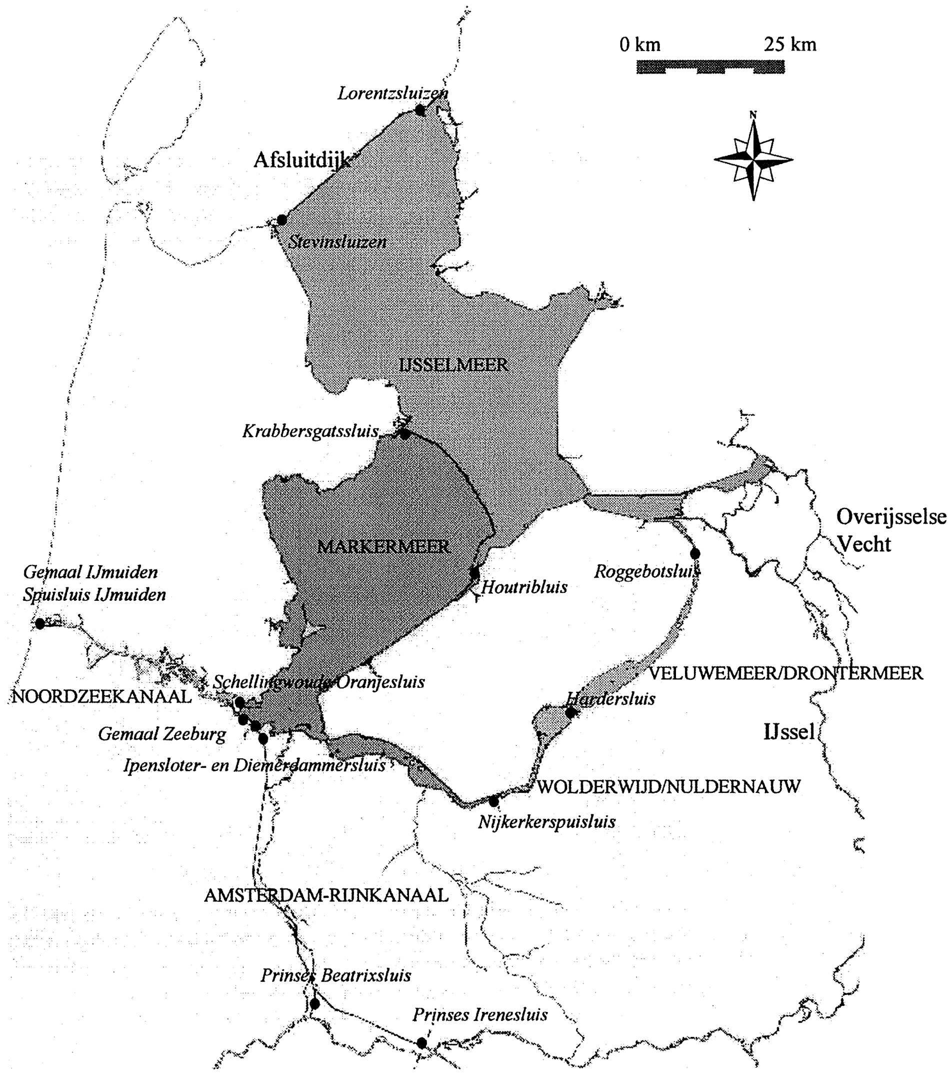


Figure 2.1 The IJsselmeer area

2.2.2 Qualitative estimation of the hydrological sensitivity to environmental change

The hydrology of the IJsselmeer Area strongly depends on the inflow of the river IJssel and the possibility to discharge into the Wadden Sea. The first aim of the water management in the lakes is to maintain the target levels. In the summer season this can easily be done, because of a lower inflow and enough discharge capacity to the Wadden Sea due to a relative high lake level. However, in winter it is hard to maintain the lower winter target level, because winter levels are relatively low.

Winter season

The lake level in the IJsselmeer is especially sensitive for changes in sea level. In general the average lake level in the IJsselmeer increases with half the sea level rise, where the extreme lake levels increase with the sea level rise. Additional increase due to increasing IJssel discharge will give an additional rise. This increase in lake levels in the IJsselmeer will then also be seen in the other lakes, however less apparent.

Summer season

In summer the lake level is less sensitive to an increase in sea level. The current target lake levels can be maintained. Problems in the summer season may arise when the inflow is lower than the water demand (agriculture, drinking and flushing water). The lake levels will then drop below target level, causing problem for the water supply. Lower lateral inflow due to a higher temperature can increase this.

2.3 The Netherlands terrestrial area

2.3.1 Hydrological setting

The terrestrial areas in the Netherlands cover the lower areas consisting of Holocene fluvial and marine deposits (clay, peat and silt) and higher areas underlain by Pleistocene glacial deposits, mixtures of clay and gravels, fluvial sands and gravels and wind blown sands. The relatively higher regions are groundwater infiltration areas, with ground water levels up to several meters below the surface. These areas receive fresh water mainly from precipitation. In summer when evaporation exceeds precipitation, water is extracted from the groundwater reservoir. These higher areas drain through the groundwater and small creeks to the lower terrestrial areas. The lower regions have upward groundwater seepage. Here, groundwater levels are artificially maintained at the surface or several tens of centimetres below it. The lower areas receive water from precipitation and partly from groundwater flow from the higher regions. They drain towards the rivers, the IJsselmeer area or directly into the sea.

2.3.2 Qualitative estimation of the hydrological sensitivity to environmental change

Land subsidence

Land subsidence has a relatively small effect on the average groundwater level (Haasnoot et al., 1999). It often leads to an increased gradient in surface elevation that accelerates both downward and upward seepage. This results in a lowering of the groundwater level in infiltration areas and higher groundwater levels in seepage areas. Changes occur only in areas where land subsidence is considerable, such as the peat areas in the province Zuid-Holland and brook valleys in the province Friesland. If the surface water levels are not lowered artificially along with land subsidence in the lower regions, groundwater levels will be higher.

Land use

Land use changes (i.e. increases of nature and forest at the expense of agriculture) may result in a change of groundwater recharge and therefore a change in groundwater levels and discharges. On a nation-wide scale these changes might be negligible, as the area where the land use is changed is relatively small. Nevertheless, on a local scale land use changes may lead to changes in groundwater levels that may be as large as the changes caused by changes in evaporation. For example, the annual evaporation in the Netherlands is on average 620 mm. A land use change of grass to cereals might result in a change in evapotranspiration of approximately 20 %, assuming no limitation of soil water availability.

Land subsidence and Sea level rise

Previous research (e.g. Oude Essink, 1996; Haasnoot et al., 1999) learns that changes in groundwater salt loads are determined by land subsidence and sea level rise, rather than by climatic changes. Changes could be up to 500kg/ha/yr. The impact of sea level rise and IJsselmeer level on groundwater levels is only relevant in the area near the North Sea shore and the lake IJsselmeer.

Precipitation

A net precipitation increase intensifies infiltration in infiltration areas and upward seepage in brook valleys. As the precipitation surplus increases, the average of the mean spring groundwater levels will rise. This effect is most apparent in the southern and eastern parts of the Netherlands. The rise of the groundwater levels strongly depends on the drainage intensity of an area. If intensities are high, the extra net precipitation is discharged into surface waters, rather than stored in the shallow groundwater system. In areas with less dense drainage, such as the Pleistocene areas in the eastern part of the Netherlands, changes in groundwater levels will be higher. In the Holocene deposits in the western part of the Netherlands (polders) groundwater levels are determined by the surface levels and water level regulation rather than by precipitation.

Consequently, the impact of climate change on groundwater levels is smaller in these areas. Model results show an average increase of 4 – 5 cm for a temperature rise of 1 °C and 10-15 cm for a temperature rise of 4 °C (Haasnoot et al., 1999). This implies that effects on groundwater levels are non-linear.

Effects of precipitation change to the mean annual drainage are straightforward. Previous research (Haasnoot et al., 1999) suggests that the changes of the annual discharge in percentages are approximately the same as the percentage of increase in winter-precipitation foreseen in a scenario.

Discharge Rhine and Meuse

As mentioned before climate change will increase the average winter runoff of the river Rhine, while the summer discharges decrease. The increase of winter discharge will affect of possibilities of draining the increased discharges from the regional water systems. In the summer period, water from the river Rhine is used for flushing the polders and minimising dry conditions. The commission "Waterbeheer 21^{e} eeuw" has used the results of the previous NRP project (Middelkoop et al., 2000), in order to model the effects of changed river discharges due to climate change on the water availability for the regional water systems. The mean annual water demand from regional water systems shows only small changes in the western part of the Netherlands. However, water demand during summer may increase in response to climate change. For example, in an extreme dry year, the water demand of district Rijnland increases from 25 m^3/s in the current situation to 32 m^3/s at a temperature increase of 1^0C and 37 m^3/s at a temperature increase of 4°C. At the same time the water availability decreases (by a smaller amount). In the same scenario district Rijnland cannot receive sufficient water over a three decades longer period each year than in the current situation. The difference between demand and supply is approximately 10 to 15 m^3/s at a temperature increase of 1^0C and 20 m^3/s at a temperature increase of 4°C.

3 Description of the models used

3.1 River basin model

3.1.1 Description of the model

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 that 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 km 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 evapotranspiration 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, or snow cover duration.

RHINEFLOW-2 continues along the lines defined in the RHINEFLOW-1 project (Van Deursen, 1999). Whereas RHINEFLOW-1 used a temporal resolution of 1 month, this time step is considered too long for a detailed study of the impacts of climate change. For a proper analysis of both problems related to the functions of the river as well as for the formulation of water management strategies, a shorter time step is considered essential. Therefore RHINEFLOW-I was improved to be able to simulate hydrological response of the Rhine basin on a 10-daily basis.

3.1.2 Concepts of the RHINEFLOW-2 model

The aim 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 time series of change in precipitation and temperature in the Rhine catchment, which will be superimposed on present precipitation and temperature time series. As for RHINEFLOW-I, RHINEFLOW-2 is developed to simulate impact of changes in the water balance components. RHINEFLOW simulates the water balance of the Rhine catchment as a series of storages in reservoirs. RHINEFLOW recognises 3 storage compartments: 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 time steps in a model run, these reservoirs are updated, representing the temporal behaviour of these storages.

Data base

The following data set is available for the RHINEFLOW-2 model:

- temperature data stations with min, max and mean 10 day station temperature;
- precipitation data stations with 10 day 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, and 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 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 sub-catchments of tributaries of the Rhine the model will produce reliable results.

Simulating processes in the snow compartment

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 characterised by a large degree of heterogeneity in the important properties controlling snow accumulation, snowmelt and meltwater runoff.

The impacts of climatic change are critical to regions with seasonal snow cover, 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.

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 periods with melting and re-freezing of water. Within catchments with the size of the Rhine basin, snow melt may occur at one location, while at the same time snowfall and accumulation may occur at other locations.
Within the snow compartment the following processes are simulated:

- snow fall;
- snow melt;
- snow storage.

The process of snowfall, -accumulation and snowmelt is governed by the available energy, 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 is based on both minimum and maximum temperature for each time step. Snowfall is determined by (1) the minimum temperature, and (2) the fraction of precipitation falling as snow, which equals the fraction of the temperature interval between minimum and maximum temperature that is below this 'snowfall trigger temperature'.
- Simulation of snowmelt is based on both minimum and maximum temperature for each time step. Snowmelt is triggered by the maximum temperature. Snowmelt is decreased for the fraction of the temperature interval that is below this 'snowmelt trigger temperature'.
- A slow flow mechanism that represents melting of glacier ice. This mechanism is necessary because the descriptions of the snow module otherwise allows a snow cover to build up for ever, thus creating a very large 'sink of water' from which water will never again become available.

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 a empirical model, with as main independent variable temperature. The use of this type of formulae for Climate Change studies results in a overestimation of potential evapotranspiration;
- the Thornthwaite-Mather equations are developed for the use in the United States. Applying these formulae in other areas may give rise to considerable problems.

Better estimates of potential evapotranspiration in the Rhine basin under current climate conditions are available from the meteorological institutes in the catchment. The task for RHINEFLOW-2 is to estimate changes in evapotranspiration as a result of 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.

3.1.3 Model parameters and variables that describe environmental change

- RHINEFLOW-II can be used to simulate impact of changes in precipitation and temperature by adaptation of the input time series.
- Changes in evapotranspiration are equally straightforward simulated, since the model uses evaporation tables as input and a relation between evaporation change and temperature change.
- 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 by changing crop factors according to values published in the scientific literature. Land use changes leading to changes in separation between direct and delayed runoff could be simulated by cautious adaptation of the separation coefficient.
- Management measures that affect flow time in the river can only be evaluated by expert judgement on the out put time series of RHINEFLOW-II, or by using this output as input in e.g. hydraulic routing models. This also counts for changes in lake management operational rules for the Swiss sub-basins.

3.2 IJsselmeer area models

3.2.1 WINBOS

The effects of climate change on the IJsselmeer Area are calculated with models that are available in WINBOS. This is a decision support system developed for the WIN-study (Iedema and Breukers, 1998; Oosterberg et al., 1998). The WIN study explores future developments in the IJsselmeer and adjacent areas. WINBOS consists of several individual models, which are coupled. WINBOS not only calculates the effect of changing climate, but also the effects of a changing water management on the water system. A case (scenario) in WINBOS comprises a set of water management rules such as target levels, climate change scenarios and water management measures. Using the water balance model BekkenWIN the lake levels and the discharges through sluices and pumping stations for a case are calculated. Using the lake levels HydraWin calculates the required crest height of the dikes. The modules for regional drainage and supply calculate if the present infrastructure is sufficient or that adjustment of the infrastructure is required. The salt concentration is calculated using the model ZoutMeren. The modules that are described in the following sections are: BekkenWin and HydraWin.

3.2.2 BekkenWin

The water balance model BekkenWin is the central module of WINBOS for hydrology and hydraulic calculations. The model BekkenWin is based on the 1-D hydraulic model SOBEK. The first version of BekkenWin was developed in 1997 (Fokkink, 1997). Modifications and updates of this first version were made in order to use the model also for this NRP-study and the WIN-study (Fokkink, 1998; Fokkink and Ellen W.van, 1997). The version of BekkenWin which operates in WINBOS is used in this study (Fokkink, 1998a; Buiteveld et al., 1999).
BekkenWin simulates the water balances for the compartments IJsselmeer, Markermeer, Noordzeekanaal/Amsterdam-Rijnkanaal, Randmeren. In BekkenWin the lakes Wolderwijd, Nuldernauw, Veluwemeer and Nuldernauw are one compartment, called Randmeren. The Hardersluis is removed, according to the situation that is planned for 2000. BekkenWin calculates the mean water levels in the compartments, the discharges through all structures and the monthly residence times for all compartments. The calculation time step is 30 minutes and the resulting output of lake levels and discharges are daily mean values. The output of BekkenWin is used in three modules: HydraWin and other water management modules.

The model uses measured discharges from the regional water systems, which are available in the database of BALANS and the discharge of the rivers IJssel and Vecht (Vliet et al., 1994). The measured data set is complete for the period 1976-1996. Before 1976 regional water discharges to and from the IJsselmeer area are lacking. The module HydraWin needs a longer simulation period then twenty years to determine reliable dike crest design levels. Therefore regional discharge data of the period 1951-1976 have been derived from precipitation-discharge-relations, based on the period 1976-1996 (Buiteveld et al., 1999). The water levels in Wadden Sea and North Sea are boundary conditions.

3.2.3 HydraWin

Within HydraWin (Fokkink, 1998b) the probabilistic model HYDRA_M calculates the design crest levels of the dikes for the IJsselmeer and Markermeer as a result of the hydraulic load. The input for HYDRA_M consists of three components:

- description of the local dike profiles, forelands and dams;
- statistical data (wind data and lake levels);
- hydraulic boundary conditions (water levels and wave conditions as a function of wind speed and direction).

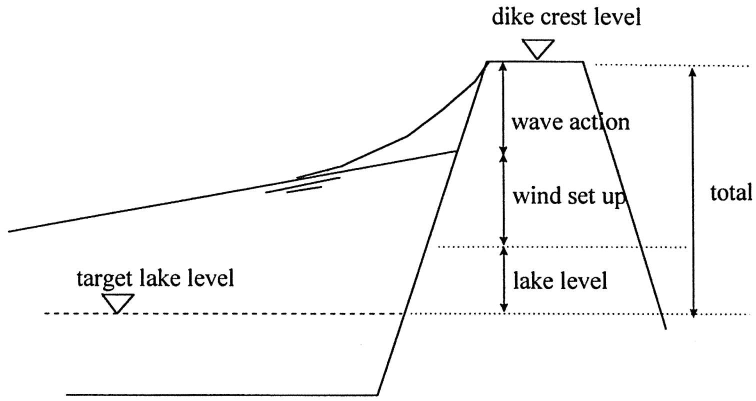


Figure 3. 1 **Determination design crest level**

The height of a dike crest design level depends of the probability that a high lake level occurs simultaneously with a storm. For a dike this is the most critical situation. HydraWin derives lake level frequency curves and lake level duration curves from the calculated daily lake levels from BekkenWin, which are referred to as *lake level statistics*. This is combined with statistical wind data (wind speed and wind direction). For the height of the wave load a certain wave set-up criterion is chosen, for example the 2%-wave set-up. Using the statistical input data of wind and lake level, and the wave set up, Hydrawin calculates a required dike crest design level for a given frequency of exceedance (Figure 3.1). The dikes bordering the IJsselmeer and Markermeer have safety standards based on annual frequencies of exceedance equal to 1/10,000 (eastern part of Markermeer), 1/1,250 (Gooi/Eemmeer) and 1/4,000 (other dikes). About 50 representative locations around IJsselmeer and Markermeer were selected for HydraWin calculations (Figure 3.2).

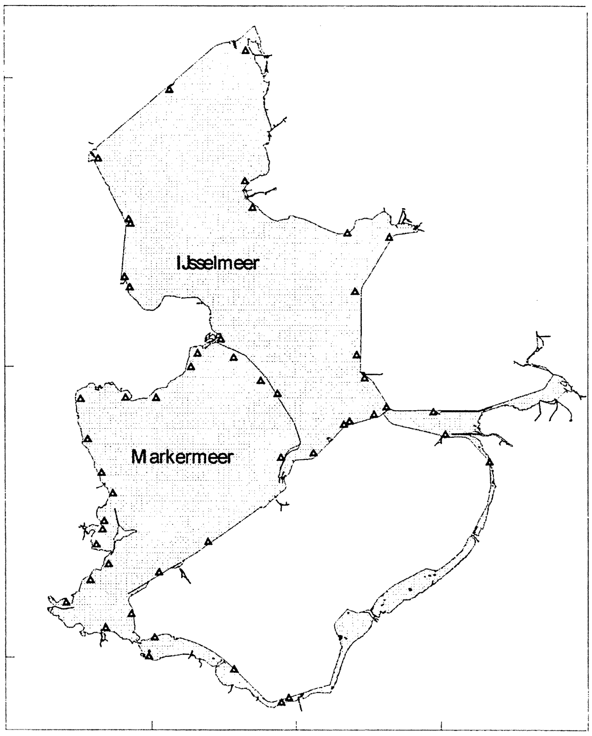


Figure 3.2 Location of dike profiles in HydraWin/WINBOS

3.2.4 Model parameters and variables that describe environmental change

Climate change is applied by changing the boundary conditions, precipitation, evapotranspiration, drainage discharge into the lakes, and intake of water from the lake.

The input for BekkenWin consist of time series of:
- water level (Tide) at IJmuiden, Den Oever and Kornwerderzand (hourly basis);
- wind speed and direction (hourly basis);
- discharge of the IJssel (daily average);
- discharge from the surrounding area (daily average);
- discharge to the surrounding area (daily average);
- precipitation;
- evaporation;

Inside WINBOS these data are transformed into data corresponding to a climate change scenario except for windspeed and direction. A sea level rise is applied to the water levels at IJmuiden, Den Oever and Kornwerderzand.

Besides the input, there are parameters that can be changed to simulate a certain management strategy:
- the target levels in the lakes, management rules;
- the capacity of the discharge sluices;
- additional pumping station to discharge from IJsselmeer into the Wadden Sea;
- pumping capacity at IJmuiden;
- the area of the Markermeer.

Input variables into HYDRAWIN are:
- the lake levels calculated with BekkenWin;
- wind statistics - frequencies and exceedence time;
- locations of specific dike profiles.

Additionally, it is possible to add a shallow foreshore.

3.3 The Netherlands Terrestrial area models

In former NRP-studies the effects of environmental changes on the terrestrial areas in the Netherlands were modelled with a set of hydrological models on a nation-wide scale. These models are:

- NAGROM (saturated zone);
- MOZART (unsaturated zone);
- MONA (connecting model interface).

The models can be used to calculate effects on regional water systems, terrestrial ecosystems and the costs and benefits for agriculture. Due to this nation-wide scale, a relatively long time is needed to run these models. Therefore a 'light' version is made of the hydrological model MOZART to carry out the sensitivity analysis.

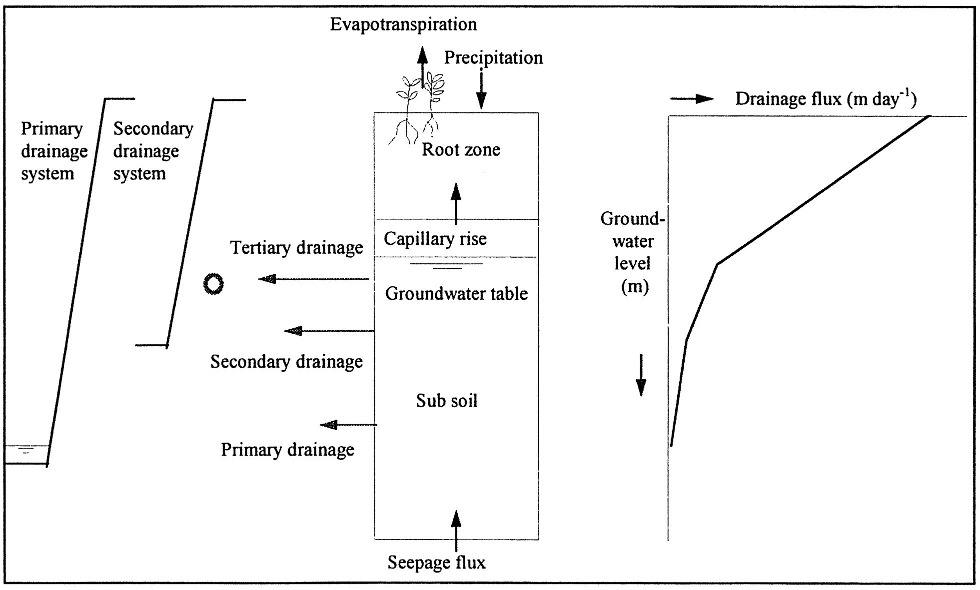
3.3.1 NAGROM

NAGROM (De Lange, 1996) is a steady state model for the saturated zone, based on the Analytic Element Method (Strack, 1989). The hydrological top system is defined as the layer above the upper semi-permeable layer. This 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.

3.3.2 MOZART

MOZART (Ontwikkelingsteam NAGROM-MOZART-DEMNAT-AGRICOM, 1997) simulates the unsaturated zone as vertical groundwater flows through a vertical soil column, which consists of an effective root soil and a subsoil. These plots coincide with gridcells of 500 m x 500 m. Groundwater flows between adjacent plots occur through the first aquifer by means of an upward or downward seepage flux. The upper boundary condition is given by ten-day-interval time series of precipitation and evapotranspiration rates. The lower boundary of the model is the seepage flux between the first aquifer and the hydrological top system through the first semi-permeable layer. Seepage fluxes are derived from the results of NAGROM using the linking tool MONA.

MOZART considers three different drainage systems, representing canals or brooks, ditches and artificial drains. For the computation of drainage, so-called drainage regulation functions have been used. These are broken linear relations between groundwater levels and the drainage fluxes. The slopes represent the drainage resistance, which is defined as the resistance between the groundwater table and the drainage system, while the intersections reflect the drainage levels. The model results include amongst others groundwater levels, surface water levels and seepage fluxes per plot, and the demand for external water supply per local surface water unit.



3.3.3 MOZART-LIGHT

The modelling of the regional water systems in the Netherlands is a relative time-consuming process and gives a lot of data. For studying the sensitivity of MOZART to environmental changes a more fast and conveniently arranged model is needed. For this purpose a simplified version (MOZART-LIGHT) is made of the schematisation used for nation-wide modelling with MOZART. In this version different parts of the Netherlands are represented by 20 plots (sites) based on the hydrological units (UC) derived from the STONE-study (Massop et al., 2000).

The homogeneous hydrological units of the STONE-study are so-called unique combinations (UC) of the following characteristics:

- geohydrological structure of the soil;
- interaction groundwater-surface water (parameterised as a relation between groundwater and a flux to drainage means).

The Netherlands are subdivided in hydrotypes, landscape regions and groundwater classes. The given spatial units are combined to the final 717 unique combinations. Massop et al. (2000) suggested that an UC may be spatially assigned to different representative parts of the Netherlands. Using the UC's the results of the sensitivity analyses can be assigned to the parts of the Netherlands where the UC's occur.

From the 717 UC's 21 UC's have been selected for the sensitivity analysis. In order to cover different hydrological areas, for each landscape regions the two most abundant UC's are selected. Also, areas with largest response to climate change and areas with important functions (agriculture, nature) have been chosen based on the former NRP results and current land use (Haasnoot et al., 1999). This gives a selection of 21 UC's representing as much as possible different important hydrological areas (higher sandy areas, polders, peat areas, brook valleys and crossing areas between infiltration and upward seepage areas) and areas with important functions.

Characteristics of the UC's have been assigned to imaginary plots of MOZART. However, not all characteristics of the STONE-study have been used. Massop et al. (2000) concluded that information on drainage intensity and fluxes provided too little variation. Therefore, the most frequently occurring drainage intensity (resistance of the soil) and flux of the nation-wide schematisation within one UC was chosen. Also, characteristics of drainage units (for example regulated or not-regulated) were derived from the nation-wide schematisation. At all sites, the land use was assumed grassland. For land use type to all sites grassland is assigned.

A comparison between the results of the MOZART model results and MOZART-LIGHT model results has been made for the reference situation (1985). The result were evaluated for the mean spring groundwater levels (MSGL). For each plot the MSGL was compared with mean, upper, and lower MSGL in the UC calculated with the original MOZART schematisation. Despite one plot, which was excluded from further evaluation, the results were acceptable From this experiment it was concluded that the 'light version' of the schematisation for MOZART is a useful tool for comparing the results of different scenarios. However absolute outcomes cannot be used.

3.3.4 MONA

The hydrological models NAGROM and MOZART are connected with the model interface MONA (Vermulst et al., 1999; De Haan, 1998). It consists of a set of Arc-Info Macro Language and Fortran programs and generates the upper boundary of NAGROM and the lower boundary of MOZART. The hydrological parameters are derived from geographical information. An up- and down scaling procedure enables proper transport of data between the two models.

Because both models depend on each other's outcomes, the computation is an iterative process. First, the hydrological top system is parameterised with drainage levels and feeding resistances with a resolution of 500 x 500 m^2, based on geographical and geohydrological information of for example elevation, surface water levels, leakage factors and transmissivity. For a first computation with NAGROM, these values are translated into effective values for the area sinks, and a continuous distribution of groundwater heads is computed based on groundwater recharge fluxes estimated from earlier model results. Subsequently, seepage fluxes can be computed from a grid with the calculated groundwater heads, the lower boundary for MOZART. Together with information on land use, reference precipitation and reference evaporation per ten-day interval, groundwater heads are the input of MOZART. Within MOZART, reference evaporation figures are transformed into evapotranspiration amounts, using crop factors, which are variable over a year and defined for five crop types (De Bruin, 1981). The geographical variation of the crop factor is obtained from a land use database.

The first computation with MOZART gives new estimates of the precipitation surplus, which is a boundary condition for a second computation with NAGROM. After a second computation with NAGROM, which gives new groundwater heads, a second computation with MOZART is carried out. When the groundwater recharges, computed by MOZART, equal the values used in NAGROM, the models are fully coupled. In that case, water balances are equal. In most cases, this occurs after two iterations. The outcome of the second run is used in determining the effects of the scenario.

3.3.5 User function models

The calculated hydrological changes can be used as input for different models that simulate the impact of hydrological changes on the different functions. These models, here referred to as *user function models*, are the ecohydrological model DEMNAT (Witte, 1997), and the agro-hydrological model AGRICOM (RIZA, 1995). These models are not reviewed in this sensitivity analysis, because their response to environmental changes is entirely depending on the hydrological models. 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.

3.3.6 Distribution model

MOZART, can be coupled to a water Distribution Model (DM; Wegner, 1981) to take changes of river discharges into account. Considering the amount of available water and the amount of water desired by different users for every hydrological section, DM simulates the stream flows in the larger rivers, canals and storage systems of the Netherlands per decade (ten-day time step). Boundary conditions for DM are the water demands computed by MOZART and the incoming river discharges of the rivers Rhine and Meuse. MOZART computes the water demands for a section per decade and after that DM considers if water quantity and quality can be delivered. If that is not possible, DM uses management rules to cut back the water demands. The national and regional water systems are schematised in DM, as a single network. This network consists of links, indicating a river or canal, and nodes, which represent locations where waterways join or water is stored or supplied. The flows of the major rivers are entered as discharges at the nodes where these rivers enter the network. Water demands of drinking water companies and industry are indicated as groundwater extraction at a node. DM completely accounts for all the water that enters and leaves the Netherlands.

3.3.7 Model parameters and variables that describe environmental change

There are several parameters and variables in MOZART and NAGROM describing environmental changes.

The following input parameters can vary with a ten-day time step:

- Precipitation;
- Evaporation (used for evaporation from lakes e.d.);
- Crop factor (used to calculate evapotranspiration);

Other parameters describing environmental change are:

- Surface water level (affect drainage regulation rules);
- Drainage resistance (affect drainage regulation rules);
- Land use;
- Management style of surface water.

Temperature change can only indirectly processed using different parameters (e.g. amount of precipitation, evaporation, crop factor). MOZART uses information on the precipitation en reference transpiration for each ten-day time-step (decade). Changes in precipitation and reference evaporation due to climate change can be applied as a percentage to the input time series. Evapotranspiration is calculated using the reference evaporation and crop factors. Crop factors depend on crop type and growing season. Climate change may change the crop factors, which in turn influences the evapotranspiration. Examples are direct effects of a rise of the atmospheric CO_2 concentration and temperature on crop growth, or an expanding growing season. Changes in crop type can be applied as well. In the previous NRP-study only five crops were distinguished (grass, cereals, other crops, deciduous forest and pine forest). It is possible to expand this with corn, potatoes, greenhouse farming, bulbs and beets.

The surface water levels of the North Sea, IJsselmeer, the estuaries and the rivers Rhine and Meuse are used as input, as they are head boundary conditions within NAGROM.

Land subsidence can be modelled indirectly by changing the surface level. In addition, adaptation of drainage levels can be applied, depending on the water management style. For example, a management style might involve adjustment of drainage levels only when a certain reclamation has been reached to reduce land subsidence. The drainage regulation rules described earlier can be used to model for example surface water level management and changes in drainage intensities.

4 Results RHINEFLOW-2 model

4.1 Parameters and variables tested

This section describes the runs that were performed for the sensitivity analysis of the RHINEFLOW-2 model. The sensitivity of the following input variables is analysed: Temperature change, defined as absolute changes in decade temperature, Precipitation change, defined as percentage change in decade precipitation and Evapotranspiration change, defined as changes in potential evapotranspiration rates.

The changes in precipitation and temperature are defined by the scenarios, and are forcing functions for the entire model. However, for the changes in potential evapotranspiration rates, things are a little bit more complex. Potential evapotranspiration rates are changing as a function of temperature, but might also change as an effect of the changed CO_2 concentrations in the atmosphere. Although there is scientific evidence for changed evaporation rates due to changing concentrations, the exact magnitude is not known. Changed evapotranspiration rates due to temperature changes are part of the simulation of RHINEFLOW-2, but the changes due to CO_2 concentration changes are not implemented in the model. With the RHINEFLOW-2 the runs as listed in table 4.1 are used for the sensitivity analysis. The runs for this sensitivity analysis are not actual climate change scenario runs. For instance, Run3 with an temperature increase of 6 degrees and no changes in precipitation does not imply we are actually define such a situation as a likely climate change scenario.

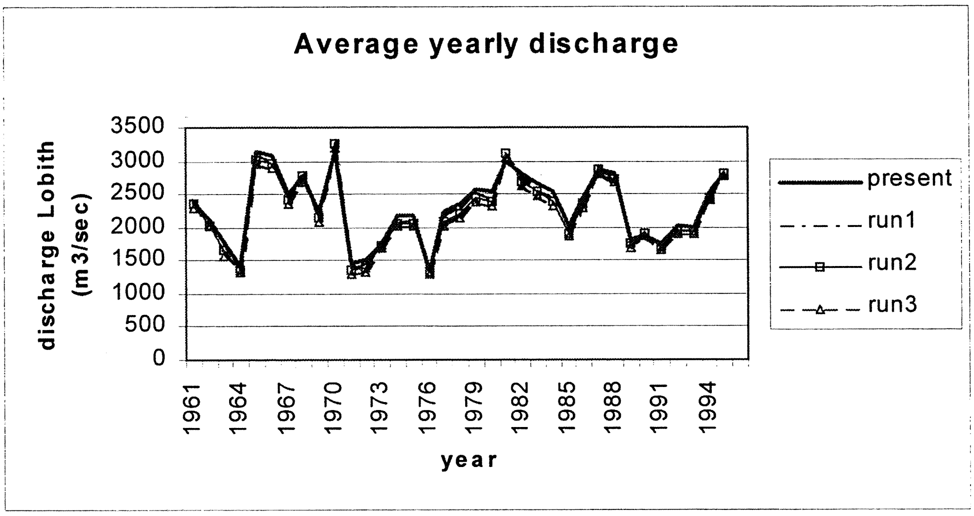
Table 4.1 Boundary conditions of the sensitivity scenarios.

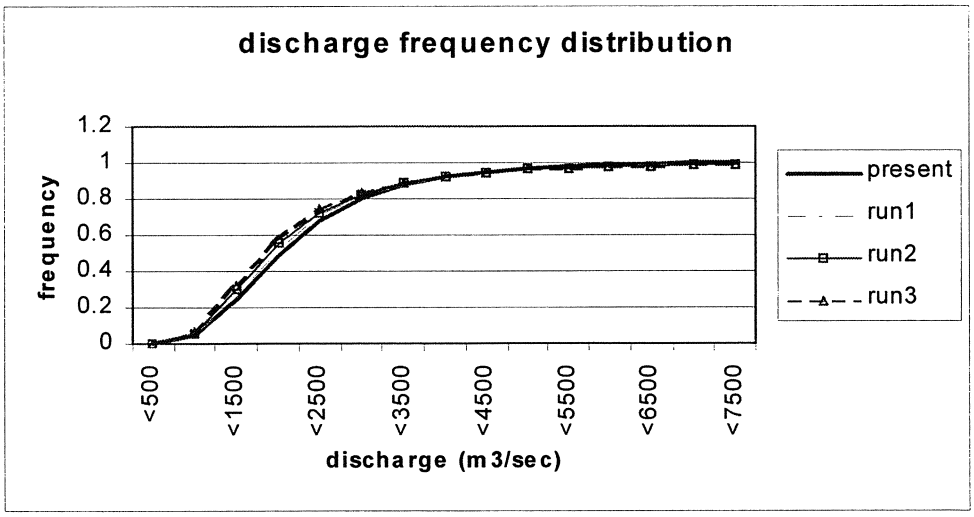
Name run	baseline	dT (^{o} Celsius)	dP (%)	dEref
Run1	-	+2	0	f(dT)
Run2	-	+4	0	f(dT)
Run3	-	+6	0	f(dT)
Run4	-	0	+50	0
Run5	-	0	+100	0
Wb2100a	-	+2	-10	+8
Wb2100b	-	+4	-10	+16
Wb2100c	-	+2	-10	0
Run6	UKHI 2100	-	-	f(dT)-30%
Run7	UKHI 2100	-	-	f(dT)+10%

4.1.1 Temperature changes

Three runs (Run1, Run2, Run3) are defined to analyse the sensitivity to temperature changes. Included in these runs are potential evapotranspiration rate changes caused by these temperature changes. The average annual and decadal runoff values resulting from these runs are given in figure 4.1 c-d. Analysing these results yields the conclusion that the sensitivity to temperature change is almost linear during several months, but not linear during springtime (snow melting), start of the winter (start of snow fall), and not linear during the end of the summer, when the difference between potential and actual evapotranspiration is increasing.

The sensitivity to temperature changes in yearly runoff is given in figure 4.1a and b. These figures show that annual discharge changes (again) nearly linear with temperature, but significant deviations from this linear sensitivity occur. As can be seen in figure 4.1b, the frequency distribution of discharges is only marginally sensitive to temperature changes.





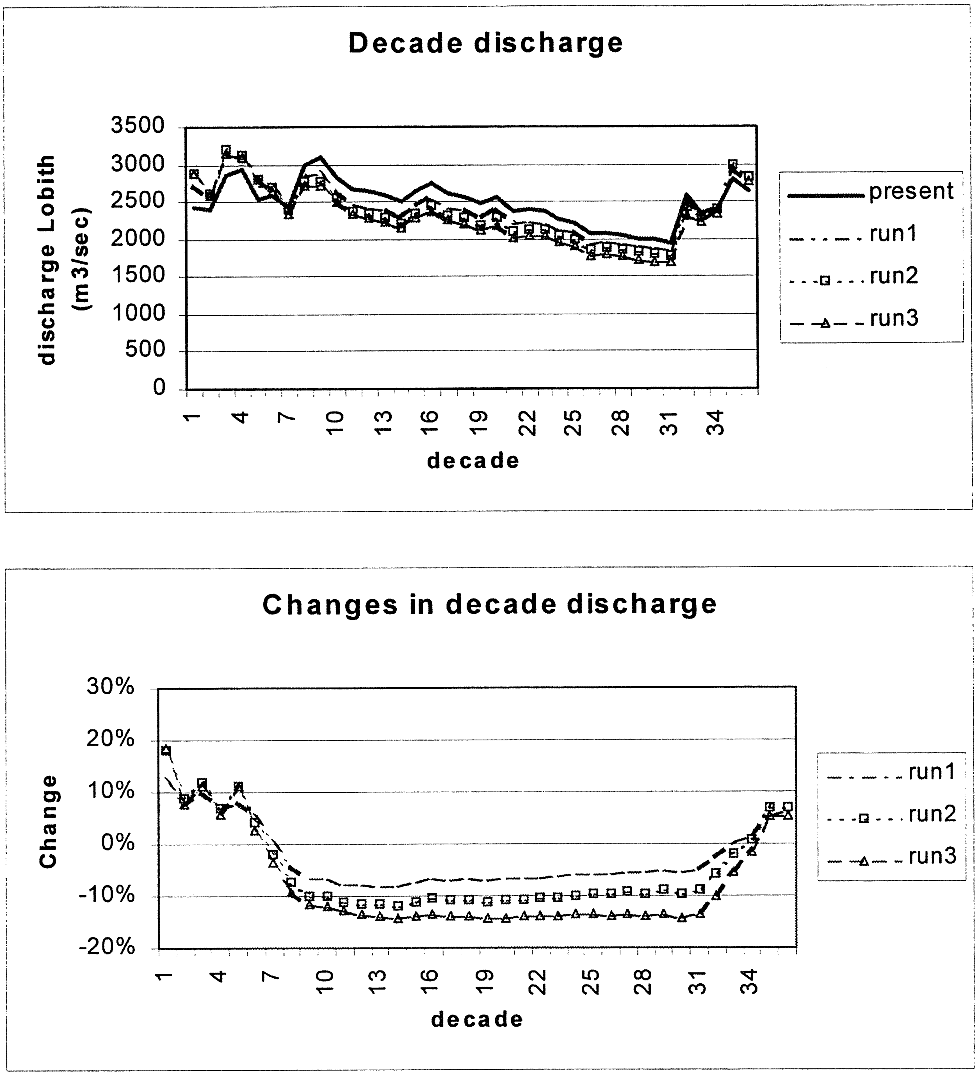
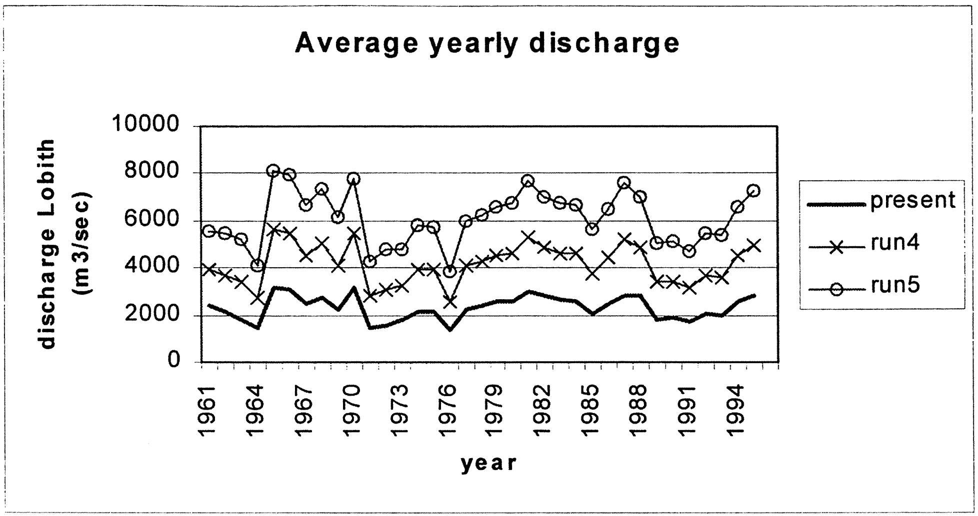
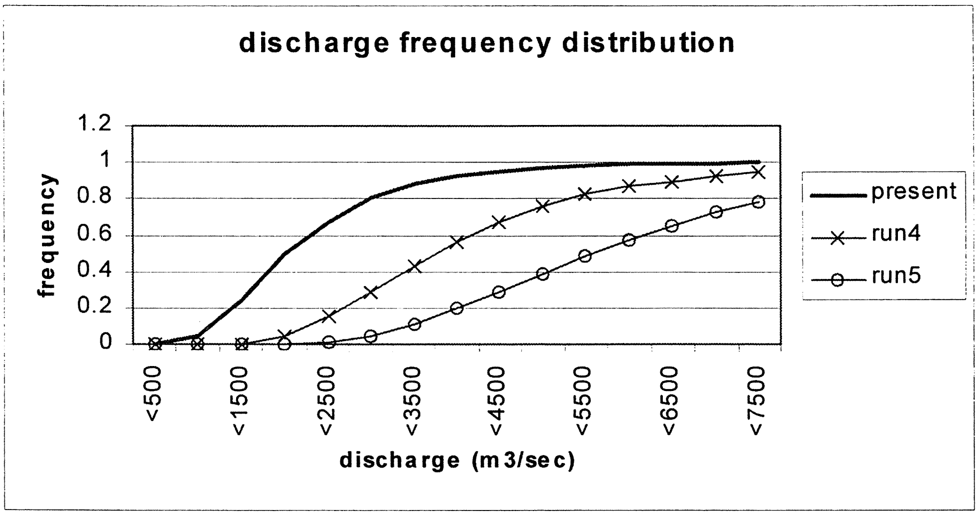


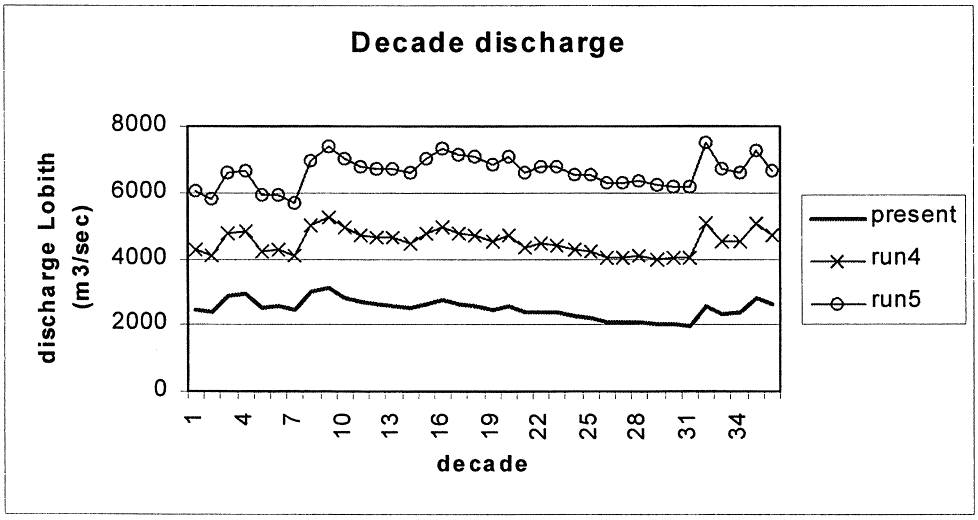
Figure 4.1. a. Average yearly discharges as a function of temperature change; b. changes in frequency distribution as a function of temperature change; c: decade discharges; d: changes in decade discharges.

4.1.2 Precipitation changes

Two runs (Run4, Run5) are defined to analyse the sensitivity of runoff to precipitation changes. The average annual runoff and average decade runoff values resulting from these runs are given in figure 4.2a and c. Analysing these results yields the conclusion that the sensitivity to precipitation is not linear. Doubling the precipitation will more than double runoff. This is because a large part of precipitation is lost to evapotranspiration. Increasing precipitation will not change evapotranspiration in the same degree, thus changes in losses from the system will be smaller. This results in a more than doubling of the runoff. Note that this analysis is only valid under the condition that the precipitation changes are positive (increases in precipitation) and large.


Average yearly discharge
discharge Lobith (m3/sec)
10000
8000
6000
4000
2000
0
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
year
present
run4
run5


discharge frequency distribution
frequency
1.2
1
0.8
0.6
0.4
0.2
0
<500
<1500
<2500
<3500
<4500
<5500
<6500
<7500
discharge (m3/sec)
present
run4
run5


Decade discharge
discharge Lobith (m3/sec)
8000
6000
4000
2000
0
1
4
7
10
13
16
19
22
25
28
31
34
decade
present
run4
run5

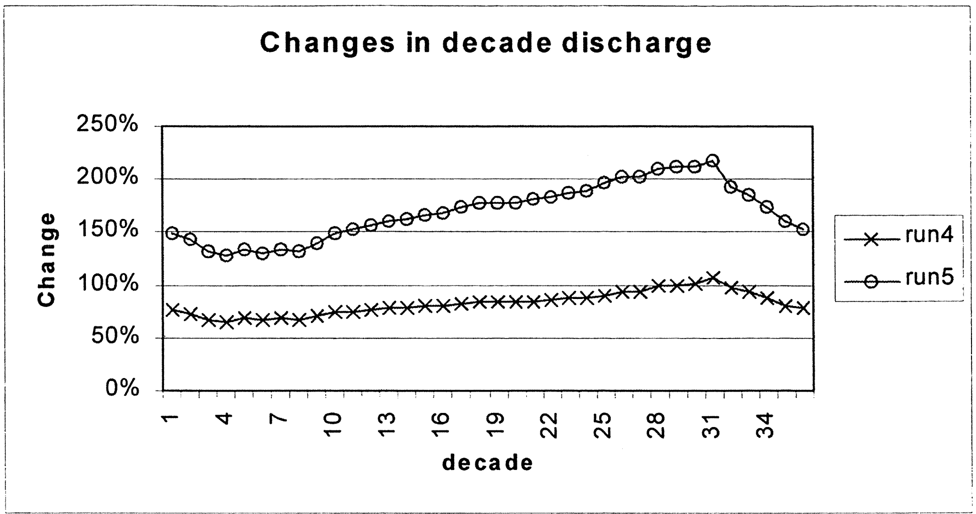


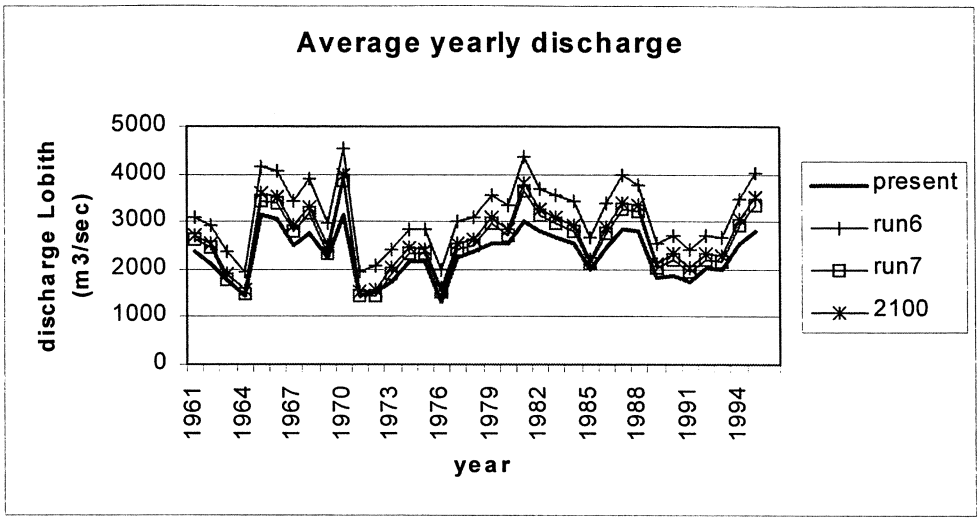
Figure 4.2. a. Average yearly discharges as a function of precipitation change; b. changes in frequency distribution as a function of precipitation change; c: decade discharges; d: changes in decade discharges

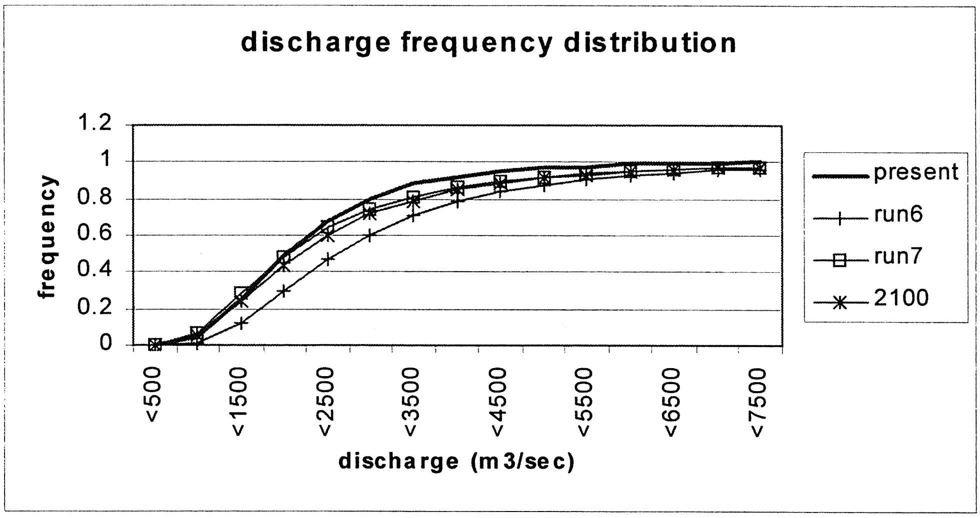
The sensitivity to precipitation changes in yearly runoff is given in figures 4.2a. Changes in yearly discharges are very much dependent on whether it was a wet or dry year. During dry years, a larger amount of the added precipitation will be used to make up for the difference between actual and potential evapotranspiration. During wet years, almost no extra water is needed for this difference, since crops are in this situation evaporating to their potential rates. All additional water thus will be added to discharges. As can be seen in figure 4.2-b, the frequency distribution of discharges is highly sensitive to precipitation changes.

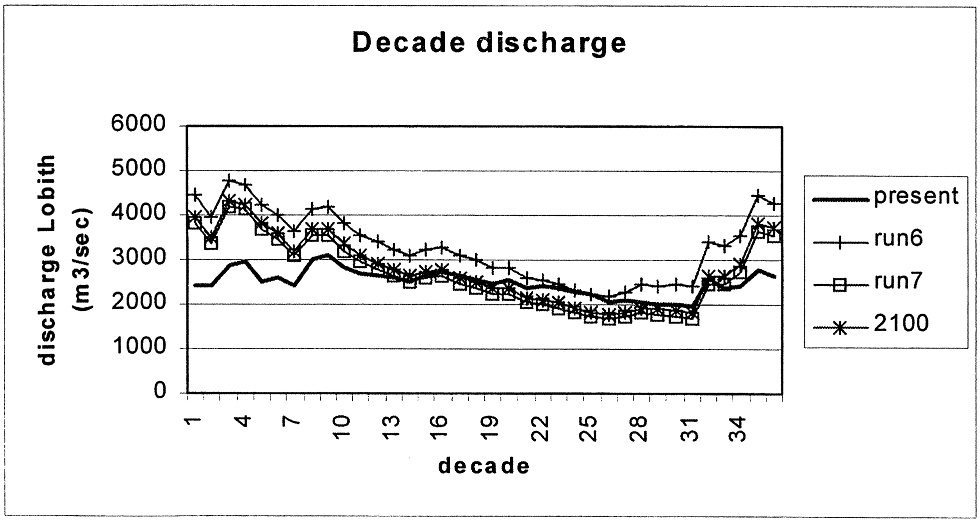
4.1.3 Changes in the evapotranspiration of crops

Two additional runs are defined to analyse the sensitivity of the model to changes in evapotranspiration. Changes in evapotranspiration will occur due to changes in temperature (the situation is analysed in an earlier section), or changes in evapotranspiration may be due to direct impact of CO_2. Because of changes in the concentrations of CO_2 in the atmosphere, the water use efficiency of vegetation may change. To analyse the combined effects of higher temperature and changed vegetation efficiency, the runs for the UKHI2100 climate change scenario were used to analyse the effects of changes in crop factor (which in RHINEFLOW-2 represent the crop efficiency). Run6 is defined as a decrease in vegetation evapotranspiration of 30%, while Run7 is defined as in increase in evapotranspiration of 10%.

As can be seen in de figure 4.3, changes in crop efficiency result in changes in losses due to evapotranspiration. These changes have a significant effect on the hydrologic cycle. Although the impact may be significant, the exact amount is currently under discussion.


Average yearly discharge
discharge Lobith (m3/sec)
5000
4000
3000
2000
1000
0
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
year
present
run6
run7
2100


discharge frequency distribution
frequency
1.2
1
0.8
0.6
0.4
0.2
0
<500
<1500
<2500
<3500
<4500
<5500
<6500
<7500
discharge (m3/sec)
present
run6
run7
2100


Decade discharge
discharge Lobith (m3/sec)
6000
5000
4000
3000
2000
1000
0
1
4
7
10
13
16
19
22
25
28
31
34
decade
present
run6
run7
2100

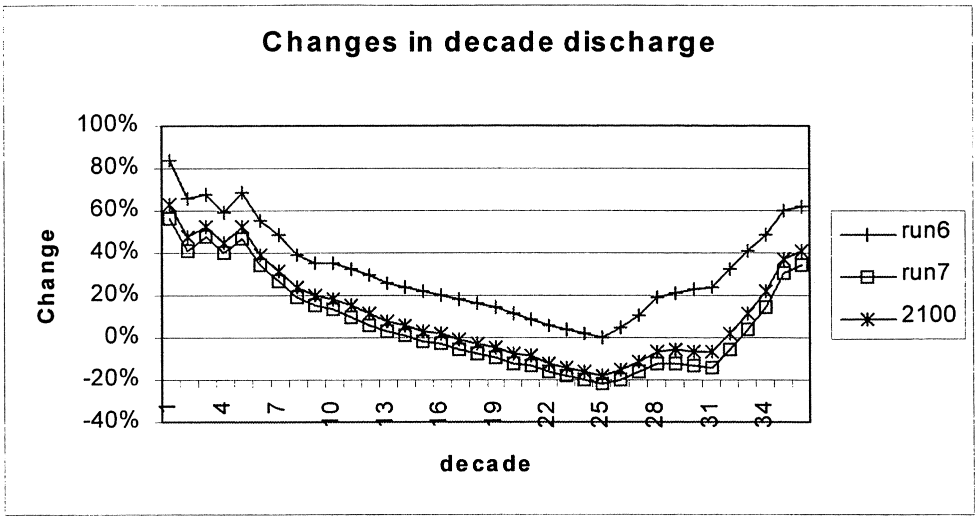
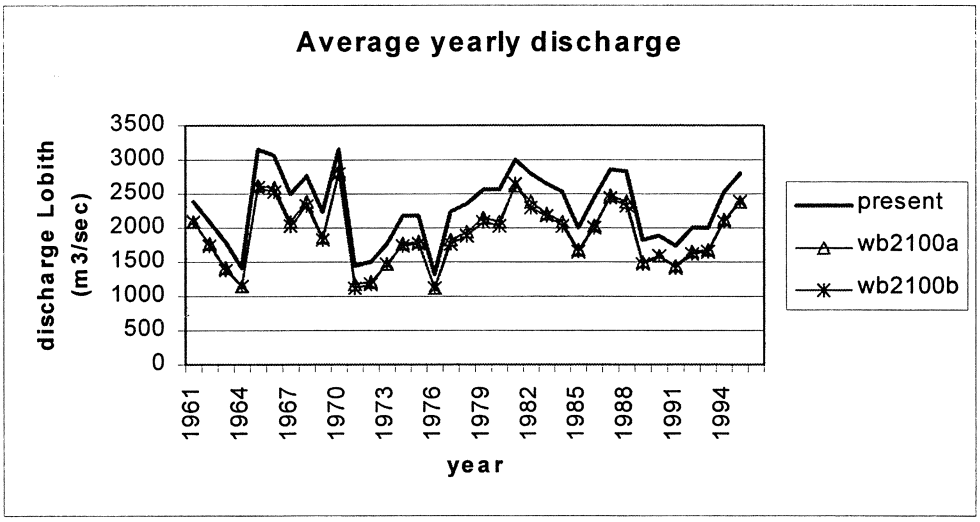
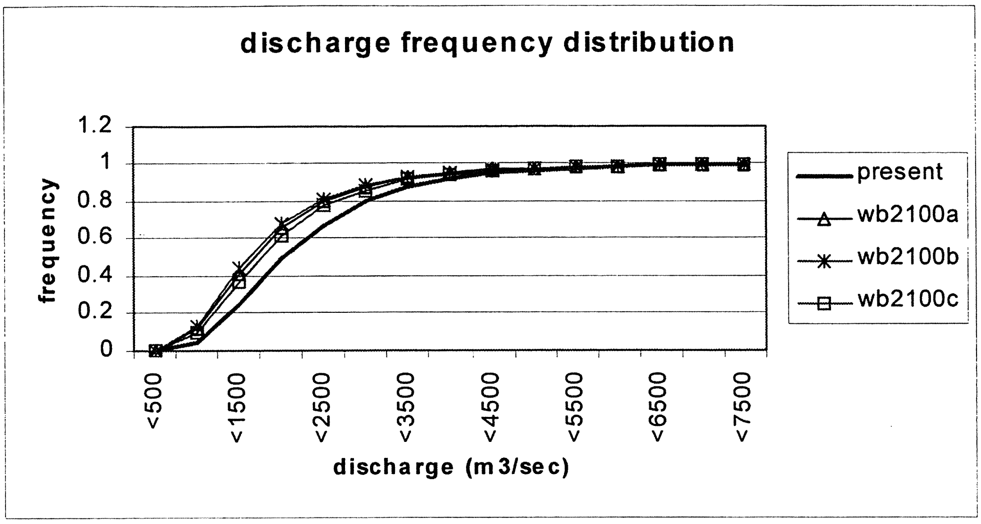


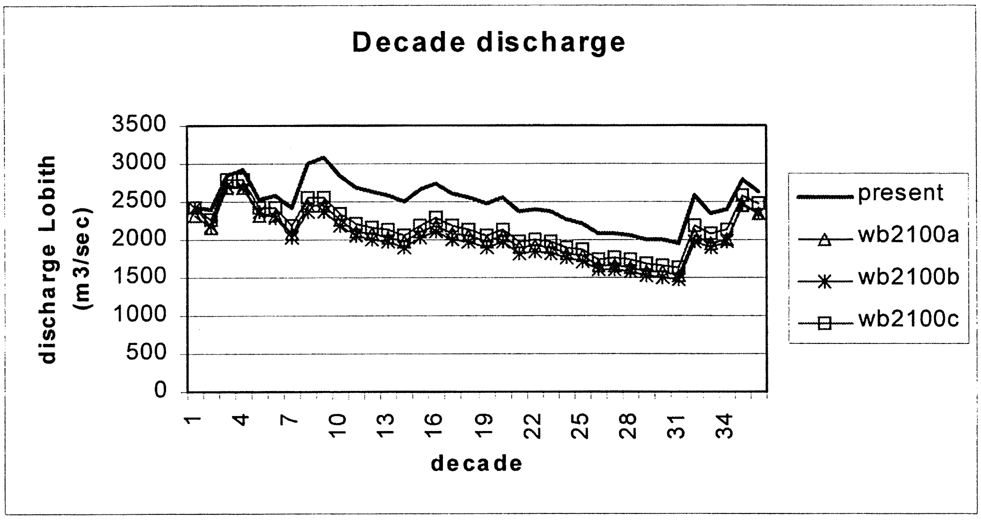
Figure 4.3. a. Average yearly discharges as a function of evapotranspiration change; b. changes in frequency distribution as a function of evapotranspiration change; c: decade discharges; d: changes in decade discharges

4.1.4 Combined effects

Three runs were defined to analyse the combined effects of temperature increase, precipitation decrease and a defined evapotranspiration change. These runs were evaluated for the commission "Waterbeheer 21^{e} eeuw". The results of these runs are summarised in figures 4.4 a-d.







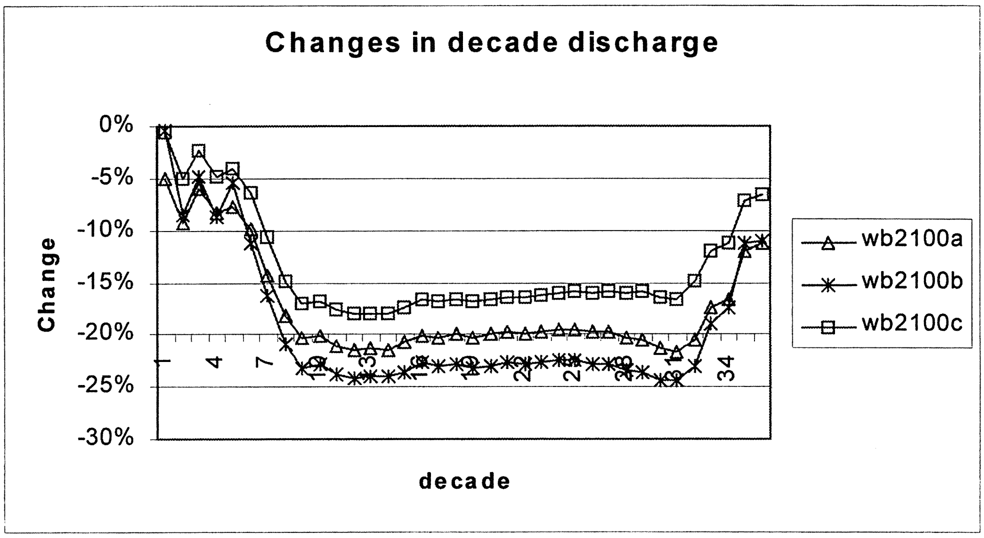


Figure 4.4. a. Average yearly discharges as a function of combined changes in temperature, precipitation and evapotranspiration; b. changes in frequency distribution; c: decade discharges; d: changes in decade discharges

5 Results IJsselmeer area models

5.1 Parameters and variables tested

The hydrology of the IJsselmeer Area depends strongly on the inflow of the river IJssel and the possibilities to discharge the water to the Sea. In table 5.1 the relative changes are given. The lake levels in the connected lakes are determined by the level in the IJsselmeer, because they discharge their water to the IJsselmeer. From these relative figures it can be seen that not all the lakes respond in the same way to a change in the water balance. The IJsselmeer and the canals are expected less sensitive to changes in precipitation and evaporation than the other lakes. However, the relative contributions of the lakes' water balance components do not directly indicate the potential effects of climate change on the lake levels. As a first indication, these can be deduced from the ratio between the total mean discharge and the area of the lake. The resulting water level fluctuations are largest in the canals, because of the relative small area. Of all lakes, the water levels in the IJsselmeer will be the most sensitive.
Because of the complexity not all the parameters for all the lakes and canals were evaluated separately. As the IJsselmeer is the most important lake we only analysed the sensitivity of this lake for separate parameters. For the other lakes only the combined effects are shown.

Table 5.1 Relative contribution (in percent) of various components to the mean water balance of different sections in the IJsselmeer area (based on the period 1976 until 1990)

	IJsselmeer		Markermeer		Border Lakes		Noordzeekanaal Amsterdam-Rijnkanaal	
flow rate into lake	summer	winter	summer	winter	summer	winter	summer	winter
precipitation (%)	6	5	15	30	17	10	1	1
river discharge (%)	87	79	8	25	22	26	4	4
pumped (%)	5	9	8	27	43	49	40	43
seepage (%)	0	0	0	0	11	8	2	2
discharge (%)	2	7	69	18	7	7	53	50
flow rate from lake								
evaporation(%)	8	1	27	9	21	2	1	0
watersupply (%)	8	1	33	18	0	0	2	2
discharge(%)	84	98	40	73	33	72	95	97
downward seepage (%)	0	0	0	0	46	26	1	1
total discharge out (m^3/s)	474	674	90	70	10	17	94	95
water slice per day (cm.).	34	49	10	8	14	23	235	239

5.1.1 Sea level, river discharge lateral inflow

Van de Slikke (1996) analysed the relative contribution of the increase in the lake level by increased sea level, river discharge and precipitation in the case of the winter season. It appeared that the sea level rise has the largest effect on the lake levels followed by the increase in the river IJssel discharge. The increase in the other terms, such as discharge of the surrounding area and direct precipitation are of less importance. The results are summarised in table 5.2.

Table 5.2. Contribution from different sources to changes in the lake levels

Lake level recurrence time (year)	UKHI2020		UKHI2050		UKHI2100	
	IJssel (%)	Sea level (%)	IJssel (%)	Sea level (%)	IJssel (%)	Sea level (%)
1	5	95	7	93	8	91
10	5	90	9	91	9	88
100	10	85	9	89	10.5	87
500	5	90	9	89	9	88

5.1.2 Wind

The sensitivity of lake level and crest height are analysed in two ways.

A. for the effect of a changing wind speed from directions between 270 to 360 degrees on the lake level of the IJsselmeer;

B. for changes in wind speed and direction on crest height of dikes.

Wind effect on lake levels

This calculation in done using Bekken_2 (Van de Slikke, 1996), with the same functionality as BekkenWin. Wind affects lake levels through drainage efficiency to the Wadden Sea. A changing wind has two effects both the wind set-up in the lake changes and the wind set-up in the Wadden Sea changes, this changes the daily period that water can be drained by gravity as well as the efficiency of the drainage towards the Wadden Sea. The effect on the IJsselmeer water levels is calculated with the model Bekken_2. The boundary condition on the Wadden Sea is the water level at the discharge sluices. Using a simple empirical relation between wind set-up and wind speed, the boundary water levels are transformed to the new wind situation.

$$\text{Change wind set-up} = 0{,}6(2*\text{wind speed\_new}/30)^2 - 0{,}6(2*\text{wind speed\_old}/30)^2$$

Using these boundary conditions effects on the average and maximum lake levels were calculated. The results of this calculation with different percentage change in wind speed are shown in table 5.3. It appears that an increasing wind speed causes little change in the lake levels.

Table 5.3 Change in average and maximum IJsselmeer lake level due to a change in the wind speed from the direction 270 until 360.

Incease windspeed (%)	average winter lake level (m NAP)	maximum lake level (m NAP)
0	-0.2519	0.365
5	-0.2513	0.37
10	-0.2508	0.371
20	-0.2494	0.376
-5	-0.2526	0.366
-10	-0.2534	0.358
-20	-0.2545	0.349

Wind effects on crest height

The calculation of the design crest height of the dikes around the IJsselmeer Area by HYDRA_M uses as input the statistics (frequency and period of exceedence) of lake levels, wind speed and wind direction. Since lake levels are not sensitive to wind speed, it is assumed that wind speed does not influence the design crest height in a direct way. The wind however also influences the process of wind set-up and waves in the lake itself. The wind statistics input into HYDRA_M has been changed in a way that is equivalent to an increase of the wind speed by 10%. The effect on the design crest height is given in table 5.4 in the case of the conditions given by the UKHI2100 scenario.

Table 5.4. Average increase in design crest level for IJsselmeer and Markermeer compared to the design crest level calculated with HYDRAWIN for present situation. For the UKHI2100 scenario with according sea level rise the results of an increase of 10% wind speed are shown in the right-hand column

climate scenario	central	central	upper	upper	
Temperature increase	1	2	4	4	
year	2050	2100	2100	2100	
				+10% windspeed	
IJsselmeer East	0.40	0.98	1.70	2.00	
IJsselmeer West	0.24	0.60	1.24	1.87	
Ketelmeer	0.18	0.52	1.05	1.99	
Markermeer West	0.27	0.82	1.82	1.98	
Markermeer East	0.12	0.40	0.93	1.30	
Gooi-Eemmeer	0.32	0.45	0.77	1.15	

The tests show that depending on the location and on the lake under consideration increasing wind speed causes an additional increase in crest height between 0.2 and 0.9 m due to wind set-up. This effect is comparable with a climate scenario of +2°.

5.2 Combined effects

The combined effect of sea level rise, increased discharge of the river IJssel and the surrounding polders and the change in precipitation and evapotranspiration has been studied in the NRP project 95020. Here a summary of the results is given (Buiteveld and Lorenz, 1999).

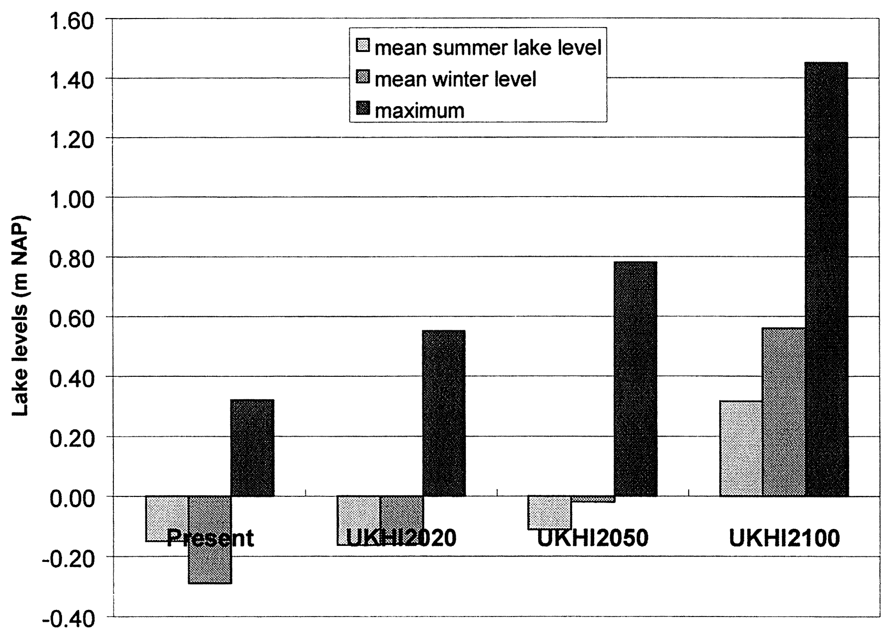


Figure 5.1 Changes in the IJsselmeer as a result of combined changes in input parameters

The water balance and the discharge possibilities of the IJsselmeer are influenced by climate change through sea level rise, changed water inflow from the IJssel river and changes in water demand and supply from the surrounding areas. The combined effects of these factors were evaluated by combining the hydrological effects of the UKHI scenario with the corresponding sea level rise. Unlikely combinations of an extreme sea level rise with minor changes in river flow were not considered.

In the winter season the discharge to the lakes increases, where in the summer season a decrease is foreseen, based on the climate scenarios used. The consequence of this is that in the winter season more water has to be discharged from the IJsselmeer into the Wadden Sea, whereas in the summer season less water has to be discharged. Without sea level rise this would already result in higher lake levels in the winter season. Lower input of water from the IJssel River in the summer season may result in lower lake levels, particularly when the input becomes lower than the water demand from the lakes.

Sea level rise will also cause an increase in lake level in the winter season. The discharge of the IJsselmeer into the Wadden Sea is only possible at low tide. An increase of the sea level will decrease the discharge capacity of the sluices in the Afsluitdijk, which will result in higher lake levels. In summer the target level is higher than in the winter season. The discharge capacity is therefore higher. Combined with a lower inflow of water through the IJssel River, sea level rise will not necessarily result in higher summer lake levels.

Using the climate change scenarios according to the UKHI GCM runs, the combined effect of a changing water balance with a sea level rise was analysed. In Figure 5.1 the changes in mean and maximum lake levels in the IJsselmeer are given for the three climate change scenarios. It appears (Slikke, 1996) that the largest part, about 90 %, of the change in lake level in winter is caused by the change in sea level. The resulting increase can for the greatest part be attributed to the change in discharge of the River IJssel. Generally, the increase in mean IJsselmeer lake level is about half the value of the sea level rise, where the maximum increase is bout the same as the sea level rise.

The water management in the IJsselmeer area is strongly guided by the lake levels in the IJsselmeer, because Randmeren and Markermeer discharge to the IJsselmeer by gravity. Higher lake levels in the IJsselmeer will cause higher levels in the other lakes as well. In the mean winter lake levels for IJsselmeer and Markermeer are shown for the UKHI2050 and UKHI2100 scenarios. The results of the UKHI2020 scenario are not shown because of the small increase in lake levels. The Randmeren, not shown in the figures, have slightly higher mean lake level than the Markermeer, because of a higher target level. However, mean lake levels of both lakes become almost the same under conditions of the UKHI2100 scenario. The levels of the Markermeer and the Randmeren do not rise as fast as the levels in the IJsselmeer. Due to the higher target level of the Randmeren lake levels are not effected directly when the sea level rise is moderate (UKHI2020). Mean lake levels in winter will become higher than the summer target level under conditions of the UKHI2050 and UKHI2100 scenario and the associated sea level rise. Generally, the dynamics in lake level will become larger in response to applied changes. Table 5.5 illustrates the lake level response to different changes in climate and sea level rise. Table 5.6 illustrates the great effect of windspeed on crest height of the dikes.

Table 5.5 Lake levels calculated with BekkenWin using the present-day water management

Mean **winter** lake level calculated with BekkenWIN					
climate scenario	present	UKHI2020	UKHI2050	UKHI2050	UKHI2100
sea level rise (m)		0.3	0.6	0.5	1.05
IJsselmeer	-0.29	-0.16	0.09	-0.02	0.56
Markermeer	-0.31	-0.20	-0.05	-0.13	0.21
Randmeren	-0.27	-0.17	-0.05	-0.13	0.21
Noordzeekanaal *	-0.40	-0.37	-0.36	-0.37	-0.36

* Noordzeekanaal mean annual values

Mean **summer** lake level calculated with BekkenWIN					
climate scenario	present	UKHI2020	UKHI2050	UKHI2050	UKHI2100
sea level rise (m)		0.3	0.6	0.5	1.05
IJsselmeer	-0.15	-0.16	-0.07	-0.11	0.32
Markermeer	-0.17	-0.21	-0.16	-0.14	0.00
Randmeren	-0.14	-0.18	-0.12	-0.13	0.01

Maximum lake level calculated with BekkenWIN					
climate scenario	present	UKHI2020	UKHI2050	UKHI2050	UKHI2100
sea level rise (m)		0.3	0.6	0.5	1.05
IJsselmeer	0.32	0.55	0.9	0.78	1.45
Markermeer	0.05	0.27	0.61	0.49	1.12
Randmeren	0.05	0.28	0.62	0.49	1.12
Noordzeekanaal	-0.05	-0.01	0.02	0.00	0.32

Table 5.6 Average increase in design crest level for IJsselmeer and Markermeer compared to the design crest level calculated with HYDRAWIN for present situation for different UKHI scenarios, and compared with an increase of 10% wind speed

climate scenario	UKHI2020	UKHI2050	UKHI2100	UKHI2100; wind speed +10%
Temp. rise (°C)	1	2	4	4
Sea Level Rise (m)	0.3	0.5	1.05	10.5
IJsselmeer East	0.40	0.98	1.70	2.00
IJsselmeer West	0.24	0.60	1.24	1.87
Ketelmeer	0.18	0.52	1.05	1.99
Markermeer East	0.12	0.40	0.93	1.30
Markermeer West	0.27	0.82	1.82	1.98
Gooi-Eemmeer	0.32	0.45	0.77	1.15

Minimum lake levels are reached in summer. These minimum levels increase with increasing climate change. In the summer water balance, less water is discharged into the lakes and more water is taken from the lakes. Consequently, the lake level can drop below target level in very dry summers. The minimum lake level in the IJsselmeer, however, will not decrease. There are two reasons for this: (1) due to the increased sea level the mean lake levels in the summer increase; (2) the lake level at the beginning of the summer half year will become increasingly higher than the summer target level.

5.3 Effect of sea level rise on the Noordzeekanaal

In figure 5.2 the effect of sea level rise on the discharge pumped to the North Sea is shown. Under the present conditions one third of the volume is discharged using the pumping station and two thirds can be discharged using the sluices. Already with a sea level rise of 0.2 m these discharges are equal and with higher sea level rise most of the water has to be discharged by pumping.
The mean level in the Noordzeekanaal does not increase very much in response to sea level rise. However, the maximum level does increase, especially according to the UKHI2100 scenario with a relative sea level rise of about 1 metre.

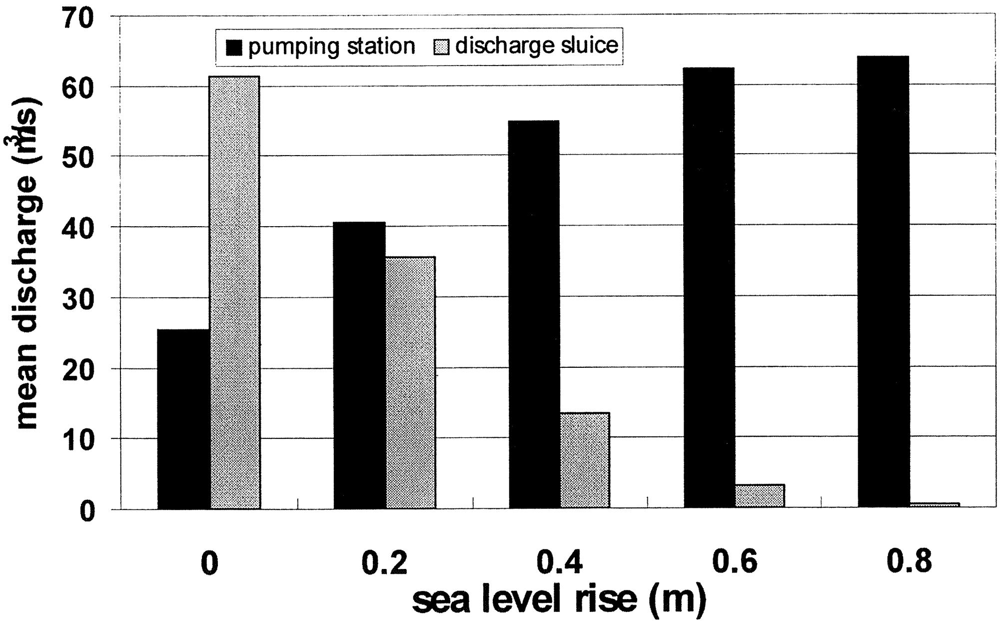


Figure 5.2 Effect of sea level rise on the discharge from the Noordzeekanaal to the North Sea by the discharge sluice and the pumping station at IJmuiden. The discharge is an average value over the period 1983 until 1995.

6 Results Terrestrial area models

6.1 Parameters and variables tested

We used the MOZART-Light model to explore the sensitivity of the hydrological system of the terrestrial area. Although this model does not cover the entire hydrological system, it excludes the models NAGROM and MONA, initial tests indicated that the results of MOZART were most relevant as this model describes the upper layer of the hydrological system and the user function models are mainly determined by MOZART. Experience from former research suggests that not considering NAGROM and MONA (deeper groundwater flows) leads to minor overestimates of infiltration in the higher areas and of upward seepage in the lower areas.
Instead of running long-term time series, as for the RHINEFLOW model and the IJsselmeer models, the sensitivity analysis in the terrestrial areas was done by application of changes on one reference year (1985). This year is considered an average year that represents the current climate conditions.

The following input variables are analysed on their effect:

- Precipitation, defined as a percentage change for each decade (10 days) during the reference year;
- Evaporation, defined as a percentage change for each decade during the reference year;
- Land use changes, defined as a change from grass to cereals, combined with an annual evaporation increase with 10 %;
- Direct effect of CO_2 on transpiration of plants, defined as a change in crop factor (similar to values from earlier NRP-studies).

Table 6.1 shows the changes in boundary conditions according to the different scenarios. Apart from above mentioned scenarios, an analysis was done to estimate how much summer precipitation should decrease to reduce the mean groundwater level in spring or the mean lowest groundwater level (Ex1 and Ex2). For this purpose existing climate scenarios have been used for changes in precipitation and evapotranspiration. These changes are relevant for agriculture and nature. Spring is the period that determines the drought damage for agriculture, because it includes the growing season and period of germination for the main part of the flora in nature areas.
The sensitivity of the hydrological models to sea level rise and land subsidence is qualitatively described earlier. The effect of land subsidence is in fact a function of the drainage regulation rules. The influence of the drainage regulation rules are described more extensively at the end of this section.

Table 6.1 Scenarios evaluated to estimate the sensitivity of the terrestrial models. The scenarios e10 and r95 are calculated assuming land use being grass or cereals. In cf_grass and cf_cereals, the crop factor has been adapted to estimate the direct effects CO_2. Climate change is assumed according to the UKHI2020 scenario. All other scenarios assume land use being grass.

scenarios							dPsummer/dPwinter	
	Precipitation change (%)	-10	0	0	10	20	-1.5/+10	-5.3/+11.3
Evaporation change (%)	-10	ep-10	e-10	e-10	e-1p1	e-1p2		
	0	p-10	r95_grass	r95_cereals	p10	p20		
	10	e1p-1	e10_grass	e10_cereals	ep10	e1p2		
	20	e2p-1	E20	e20	e2p1	ep20		
cropfactor	UKHI2020		cf_grass	cf_cereals				
cropfactor and E_reference	EUKHI2020						ex1	ex2

The results have been analysed by comparison of changes in mean spring groundwater level (MSGL), mean highest groundwater level (MHGL) and mean lowest groundwater level (MLGL). The MHGL and MLGL are derived by taking five most extreme values, respectively the highest for the MHGL and lowest for the MLGL. The MLGL represents the groundwater level in summer and the MHGL represents the situation in winter. An empirical relation is used to calculate the mean spring groundwater levels (MSGL) from the MHGL and MLGL. Approximately, the value for MSGL is determined for 80% by the MHGL and 20% by the MLGL. Also, the variation in groundwater level through the year has been used as additional information to interpret changes in MSGL, MHGL and MLGL. These variables are input to the models that estimate the effects on agriculture and nature (AGRICOM, DEMNAT).

6.1.1 Precipitation

The sensitivity to changes in precipitation is analysed using three scenarios; -10%, +10% and +20%. The MSGL change averaged over all MOZART-LIGHT plots has a mean of –12, +7 and +12 cm respectively for the different runs. However, the variation among the plots is large. For example, the effect of a precipitation decrease with 10% may locally vary from –0,6 to +52 cm. Largest changes are always found at the plots representing the sandy ridges, dunes and other sandy areas with mainly deeper groundwater levels. Smaller changes are obtained for plots representing reclaimed lakes and peat areas. In most of these areas the groundwater levels are regulated by artificially maintained surface water levels. Plots representing brook valleys and polders near the Meuse and Rhine branches show changes that lie in between the extremes.

The sensitivity of the MHGL is larger than the sensitivity of the MSGL. Furthermore, the MHGL is more affected by precipitation than the MLGL. This is because MHGL occurs in the period with the largest amounts of precipitation, when the soil is nearly saturated. A 10 % change in the period of the MHGL results therefore in a larger groundwater recharge than a precipitation change in the period of the MLGL.

Figure 6.1 shows that the change in MSGL resulting from scenario P20 is twice as large as obtained using scenario P10. This suggests a linear response of MSGL to precipitation variations (ranging between 10% and 20%) for most plots However, figure 6.2 shows the changes in MSGL obtained for a 10% decrease and a 10% increase in precipitation respectively (P10 and P-10). This figure suggests only a linear relation for plots with small changes in MSGL. For larger changes, four of five plots show larger changes at run P-10 than at P+10. Plots representing a sensitive hydrological system suggest a non-linear response between a precipitation change of -10 to +10 %. A more extensive study of the calculated groundwater levels shows that the response is determined by the shape of the drainage regulation function. A more detailed description of the effect of this function is given in section 3.3.2.

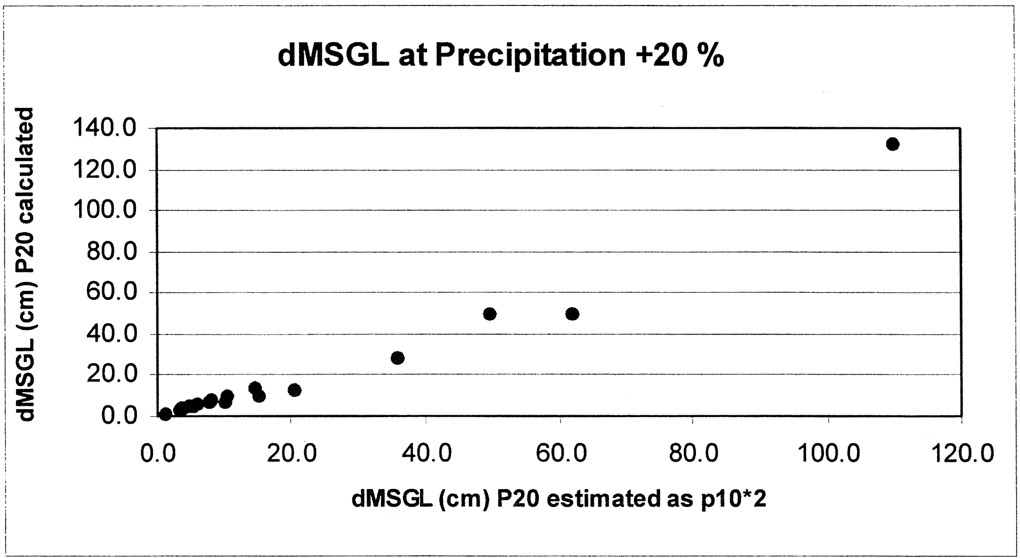


Figure 6.1 Calculated change of MSGL at an increase in precipitation of 20% (scenario P20) against an estimated value for P20 as the calculated value for scenario P10 multiplied with two. Each dot represents a different plot.

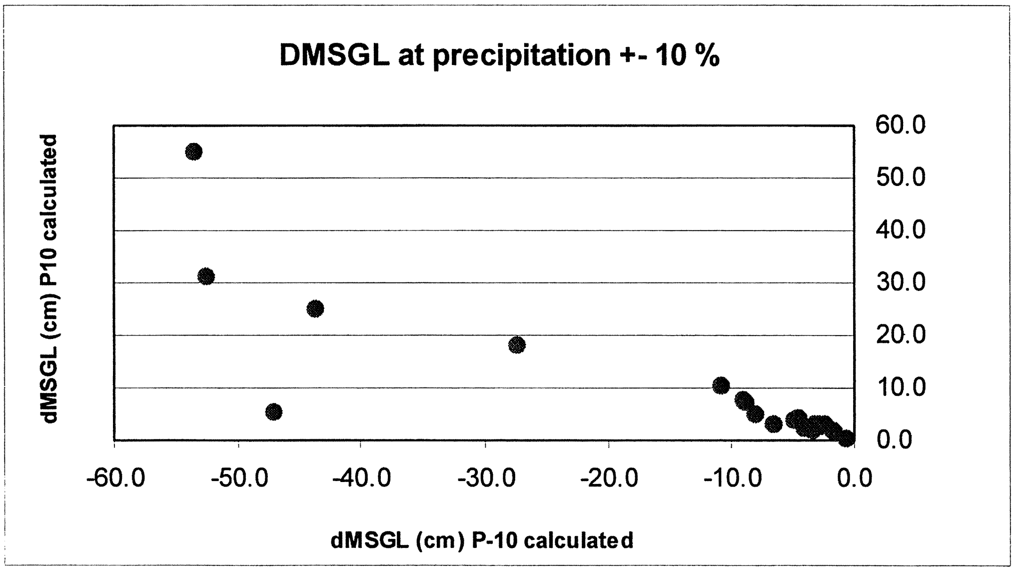


Figure 6.2 Calculated change of MSGL from scenario P-10 against scenario P10.

The runs Ex1 and Ex2 were done to evaluate the effect of a summer precipitation decrease on the mean groundwater level in spring as well as on the mean lowest groundwater level. Both scenarios envisage an increase of the MSGL, despite the decreasing summer precipitation. This MSGL is used as input for the eco-hydrological model DEMNAT in order to compute changes of nature values in the Netherlands. According to this model even a decrease of the summer-precipitation with 5% has no adverse effect on the nature values in the Netherlands. This suggests that effects of precipitation decreases in summer on groundwater levels, and thus on nature values, might be compensated for by increased winter precipitation.
The MLGL decreases according to both scenarios, especially in peat areas, river areas and reclaimed lakes (more than 10 cm for scenario 'Ex1' and more than 20 cm for scenario Ex2'). Smaller changes are found in plots representing the areas underlain by marine clay and rain-fed moors. The temporal distribution of the groundwater level changes suggests that the decrease occurs between July and October (decade 20 to 29) when using 1985 as reference year. As this period falls outside the main growing and germinating period, this may be less harmful for nature. Contrary to effects on nature, the effects of a decrease of the summer precipitation on agriculture will appear from the results of AGRICOM, as MLGL is input for this model. A decrease of the MLGL will result in an increase of the damage caused by dry conditions.

6.1.2 Evaporation

The sensitivity of the results to changes in evaporation is analysed with three scenarios; -10%, +10% and +20%. Largest changes are shown by plots representing marine clay areas (UC 688), sandy ridges (UCs 469, 449) and other sandy areas (UCs 520, 577) or areas from the Pleistocene part (UC 262) of the Netherlands The changes range from –13 to –64 cm for run E+20 and 3 to 20 cm for run E-10. Table 6.2 shows the results for the change in MSGL for the different plots assuming different P and EP scenarios.

Table 6.2 Results for the change in MSGL for the different plots assuming different P and EP scenarios.

Codes		UC-description		change in MSGL (cm) for extreme scenarios					
UC-code	plotnr	UC-regio	UC-hydrotype	**E-10**	**E+20**	**P-10**	**P20**	**EP-10**	**EP20**
30	46853	Reclaimed lakes	Westland-DC-profile	1	-3	-3	5	-1	3
25	49516	Reclaimed lakes	Westland-D-profile	3	-65	-47	10	-6	5
65	74831	Dunes	Dune area	20	-35	-54	132	-36	73
80	39987	Dunes	Westland-DC-profile	4	-7	-8	7	-5	5
129	25033	High moorland	Singraven-brook valleys	5	-10	-9	10	-4	7
142	11796	High moorland	Westland-DH-profile	1	-2	-2	4	-1	2
229	75607	Fenland	Westland-DHC-profile	2	-2	-2	5	-1	3
222	31655	Fenland	Westland-DH-profile	5	-13	-11	12	-3	12
262	27555	Pleistocene areas	Eem en/of keileemprofile	12	-30	-44	49	-28	30
287	35613	Pleistocene areas	Open profile	6	-14	-27	28	-12	23
387	90646	River areas	Westland-C-profile	1	-1	-2	3	-1	2
418	66554	River areas	Westland-H-profile	0	-1	-1	1	0	1
449	54110	Sandy ridges	Keileem profile	1	-4	-3	4	-2	2
469	84392	Sandy ridges	Sandy ridges	2	-2	-9	14	-6	12

Codes		UC-description		change in MSGL (cm) for extreme scenarios					
UC-code	plotnr	UC-regio	UC-hydrotype	E-10	E+20	P-10	P20	EP-10	EP20
520	76458	Sandy areas	Betuwe-stroomruggronden	2	-3	-7	6	-4	3
577	23388	Sandy areas	Peeloo profile	1	-5	-4	5	-1	2
582	111698	Sandy areas	Singraven-brook valleys	1	-3	-5	7	-4	4
608	133605	Sandy areas	Westland-D-profile	2	-3	-3	5	-2	3
655	10596	Marine clay areas	Peeloo profile	13	-42	-52	50	-30	34
668	113307	Marine clay areas	Tegelen/Kedichem profile	1	-3	-3	6	-2	3
697	131453	Marine clay areas	Westland-DH-profile	2	-4	-5	8	-2	4

Figure 6.3 shows the changes in MSGL simulated with the MOZART-light model for an increase of evaporation with 10% against a decrease of 10%. As can be seen from this figure 6.3 the absolute changes caused by a –10 are mostly the same as those obtained for a +10 % change of evaporation, except for two plots (UC-25: reclaimed lake; UC-655: Marine clay area). This indicates that the response to changes in evapotranspiration is linear in most cases.

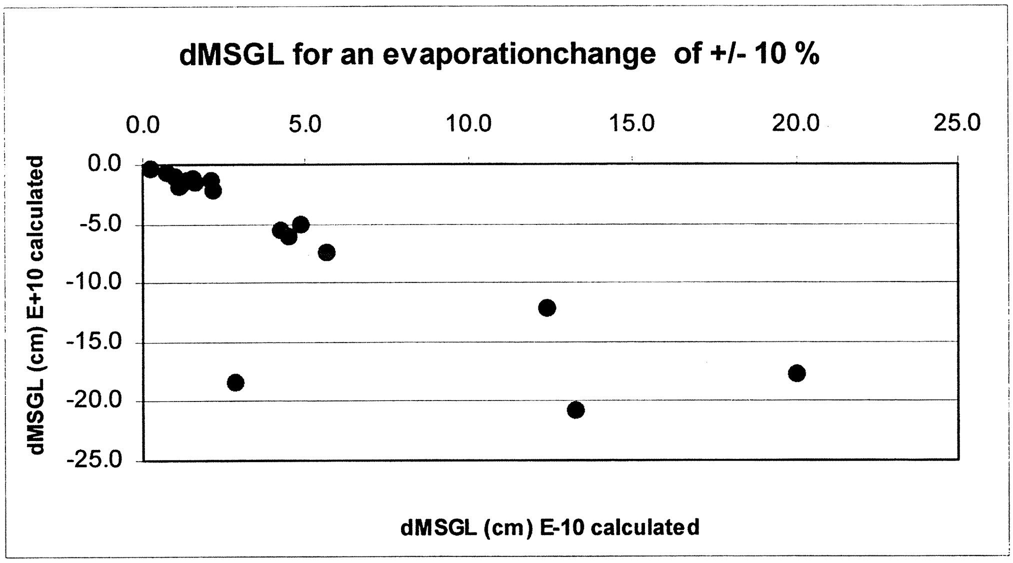


Figure 6.3 Calculated change of MSGL from scenario E-10 against scenario E10.

Analysing the temporal variation of groundwater levels MHGL and MLGL learns that evaporation has a larger effect in summer. The MLGL is more affected by changes in evaporation than the MHGL. This behaviour can be explained by the fact that the MLGL is determined by the lowest groundwater levels that occur mainly in the summer period. In this period the relatively change in evaporation, compared to precipitation is larger than in the wetter periods of the year.

6.1.3 Land use

Changes in land use may lead to changes in simulated groundwater recharge as a result of a different crop factor. To estimate the sensitivity of changes in land use we changed the land use type from grass into cereals for all plots. In general, cereals have a lower crop factor then grass, resulting in a lower transpiration and consequently higher groundwater levels.

The mean spring groundwater level shows changes from 0-5 cm in the polders to 12-25 cm in the sandy and sea-clay areas in the eastern and southern part of the Netherlands.

The variation of the groundwater level through the year (Figure 6.4) illustrates the effect of differences in crop factor for cereals and grass. Also, effects of the growing season can be traced. From decade 17 to 21 scenario r95_cereals has a lower groundwater level then scenario r95_grass, while in the other decades the groundwater level of cereals is higher.

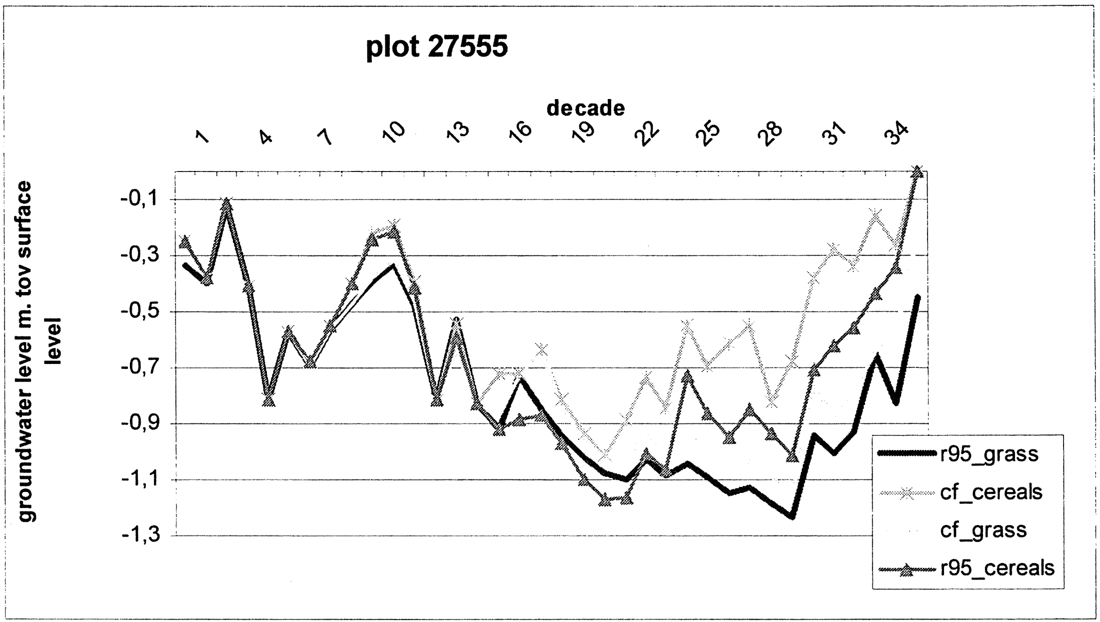


Figure 6.4 Example of the variation of the groundwater level through the year, considering the direct effect of CO_2 and changes in crop factor.

Figure 6.4 illustrates that changes in MSGL caused by a land use change from grass to cereals are only a few centimetres more than a (large!) decrease of 20% in evaporation. This example suggests that changes in land use are significant when compared to a change in evaporation.

6.1.4 Direct CO_2 effects on transpiration

In the models used, the direct effect of CO_2 on the transpiration by plants is defined as a decrease in crop factor. This means that the effect on transpiration can be linearly combined with changes in crop type. The decreases were obtained from several other studies and were already used and described in the earlier NRP-study (Haasnoot et al, 1999). Depending on the crop type the changes vary from –5 % to –15%. For grass and cereals a decrease of 5% and 15% is considered. However, these decreases are uncertain; different studies suggest different changes, depending on the increase of crop growth, which in turn is determined by the amount of available nutrients and a decrease of stomatal resistance.

A decrease in transpiration due to an increase of atmospheric CO_2 results in an increase of the mean spring groundwater levels for all plots. For plots with grass the changes range from 0 to 7 cm, while the results for cereals range from 0 to 16 cm. The changes are relatively small, compared to effect of changes in land use or evaporation. For grass the effects of a change in crop factor according to the UKHI2020 scenario is approximately 20% of the effects of a decrease of evaporation with 10 %. For cereals this percentage is about 35 %. From the variation of the groundwater level through the year it appears that the differences will show especially in summer period (figure 6.4). Plots representing dunes, sandy ridges and river areas show the largest changes.

6.2 Combined effects

Eight runs were defined to analyse the combined effect of precipitation and evaporation. In four scenarios, including the reference scenario, the changes in terms of percentage for evaporation and precipitation are the same.

The combination scenarios obtain the same conclusion as the separated runs, largest changes are always found at the sites representing the sandy ridges, dunes and other sandy areas with mainly deeper groundwater levels, while smaller changes are shown by plots representing the reclaimed lakes and peat areas. Table 6.3 shows a summary of these changes. According to scenarios where the evaporation and precipitation change with the same percentage (EP-10, EP10 and EP20) the effect of precipitation is most apparent on the MHGL and the MSGL. This can be explained by the sensitivity of the MHGL to changes in precipitation described earlier and by the sensitivity of the MSGL that is for approximately 80% determined by the MHGL.

In general, an increase of precipitation results in a larger increase MSGL than the same decrease of evaporation. Under grassland, a decrease of 10% in precipitation leads to an equivalent decrease of the total groundwater recharge for the reference year as an increase of 15% in (potential) evaporation. The effect of precipitation on MSGL is 1.5 to 25 greater than a comparable change in evaporation.

The type of response depends strongly on the plot characteristics. Approximately half of the plots show a linear relation between precipitation and evaporation within the range of changes calculated. Figures 6.5 and 6.6 show an example of the results of all scenarios for two different sites; one reacting linear and one reacting non-linear. This gives an idea of the diversity in responses. In table 6.3 an indication of the linearity is given for all plots.

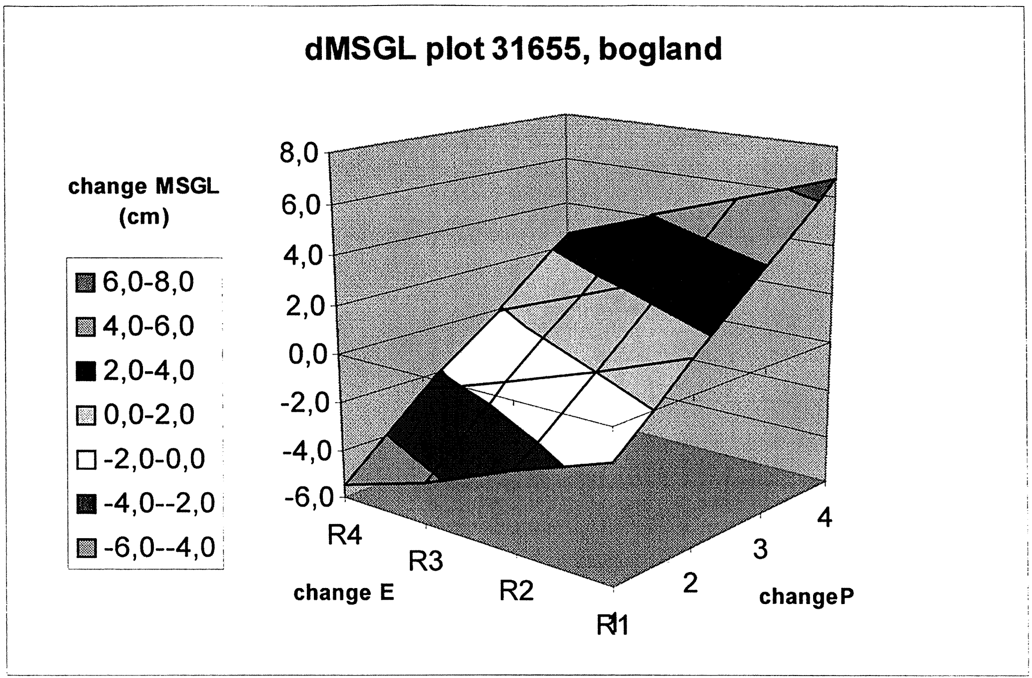


Figure 6.5 Combined effects of precipitation and evapotranspiration changes for peat land

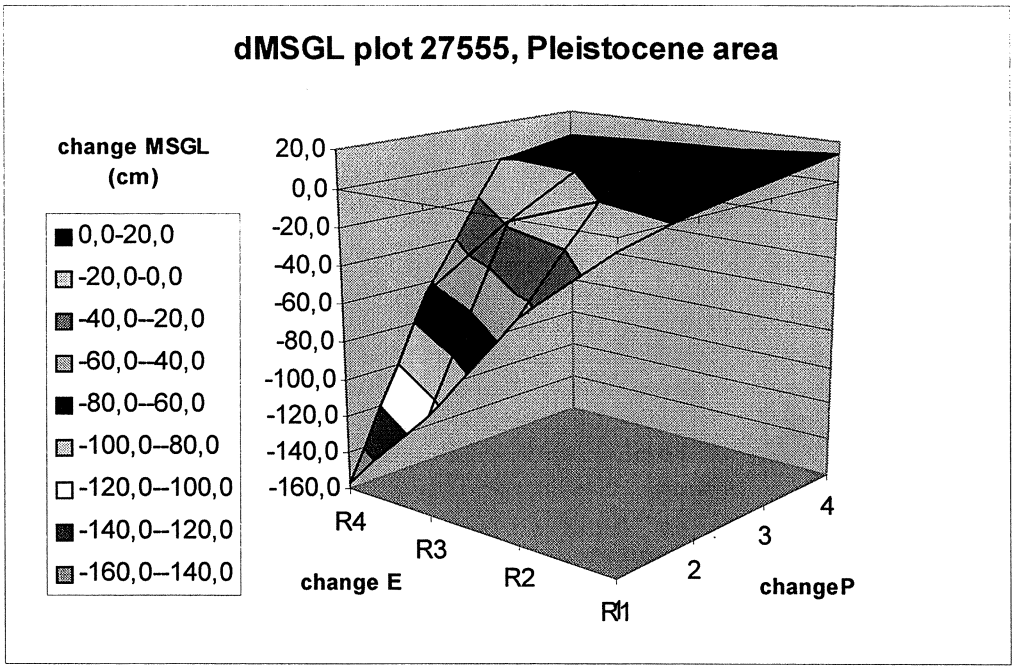


Figure 6.6 Combined effects of precipitation and evapotranspiration changes for the Pleistocene area

The MHGL is determined in the period of the year (winter) with the largest effective precipitation, also resulting in a higher sensitivity to changes in precipitation. On the other hand the MLGL, occurring in summer, is more determined by changes in evaporation. For scenarios where the evaporation and precipitation change with the same percentage percentage (EP-10, EP10 and EP20) the effect of precipitation is most apparent for the MHGL, while the change of evaporation is most apparent for the MLGL.

Consequently, it is possible that the MHGL increases, while in the same scenario (for example 'EP20') the MLGL decreases. The sensitivity of the MHGL and MLGL to precipitation and evaporation respectively leads also to larger changes of MHGL.

In the figures 6.7 and 6.8 the y-axis show the change in MSGL according to the MOZART-Light model with a combined input of a precipitation change and an evaporation increase of both 10 and 20%. The changes in MSGL calculated the results of separate runs of precipitation and evapotranspiration changes are plotted on the x-axis. For changes in E and P not larger than 10%, their combined effect might be calculated by adding the individual results without obtaining too large errors. However, for changes in the order of 20% the combined effect of precipitation and evapotranspiration may not be calculated as a linear combination from the two individual results for about half of the plots.

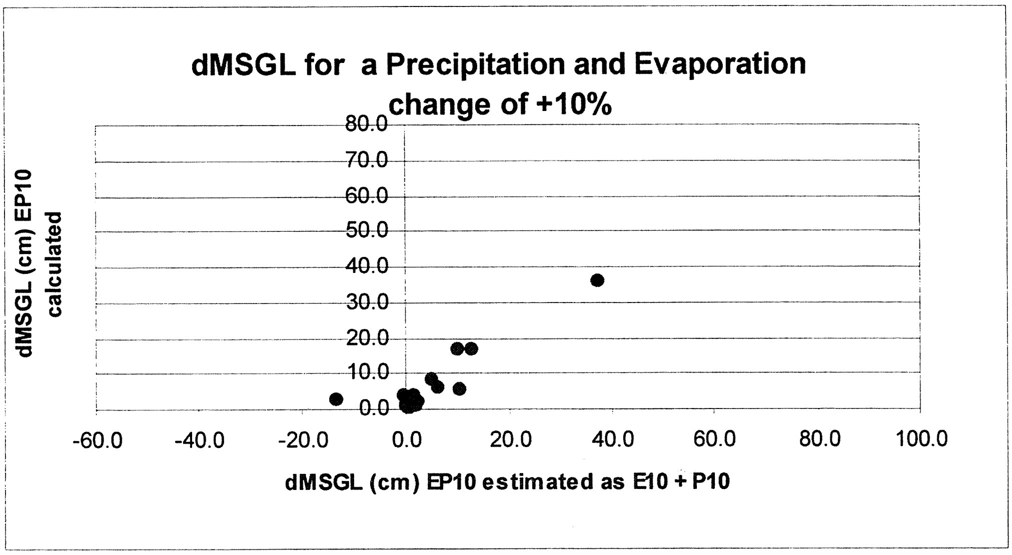


Figure 6.7 Changes in mean Spring Groundwater Level according to a combined scenario of 10% rise in EP and P and separate scenarios of EP and P rise of 10%.

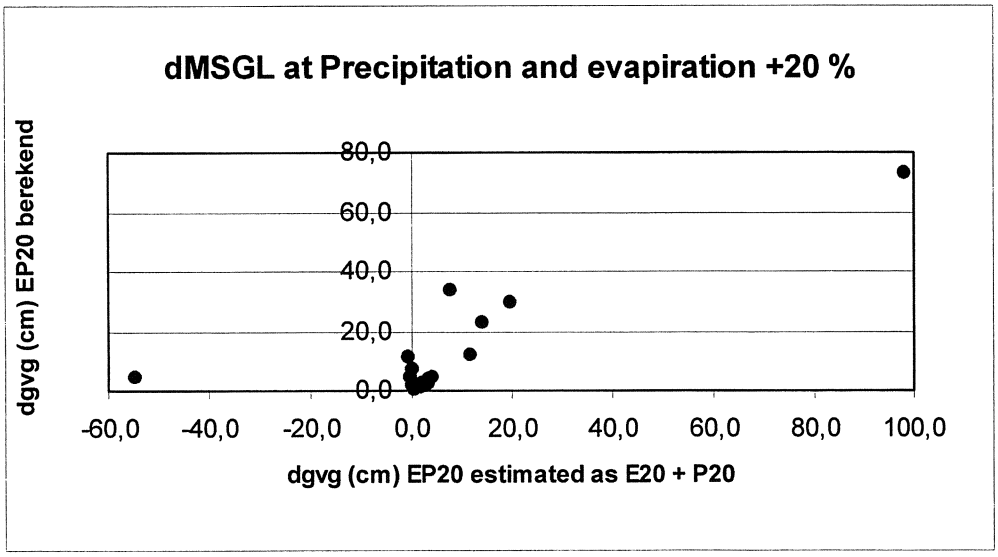


Figure 6.8 Changes in mean Spring Groundwater Level according to a combined scenario of 20% rise in EP and P and separate scenarios of EP and P rise of 20%.

The results for the changes in MHGL and MLGL show a less linear response than the changes in MSGL. Consequently, possibilities for extrapolating scenarios or combining scenarios in order to estimate the results of other scenarios are even smaller than for the MSGL.

6.3 Interpretation and conclusions

The mean spring groundwater level (MSGL) of all plots is more sensitive to changes in precipitation than to changes in evaporation. Plots representing areas where surface water levels are not regulated, such as the cover sand areas, sandy ridges, dunes, Pleistocene areas and river areas respond stronger to a change in precipitation or evaporation. Less sensitive are plots representing areas having regulated surface water levels, such as polders and peat areas.
Considering all scenarios it appears that the sensitivity of the MSGL to changes in groundwater recharge are mainly determined by the:

- shape of the drainage regulation functions (drainage depth and resistance);
- current groundwater level.

Approximately half of the plots the MSGL responds linearly to precipitation or evaporation change within the range evaluated. The plots representing reclaimed lakes (30, 25) and sandy areas (577, 582, 608) illustrate this conclusion. Also other UC show this relation (65, 129, 222, 287, 387, 697). The relation holds when the changes of the groundwater level stay within one layer (primary, secondary or tertiary system) of the drainage regulation function or in plots where for the different layers nearly the same drainage resistances are assumed.

On the other hand there are plots where the local geohydrological conditions result in changes that are strongly non-linear. This accounts for UCs 80, 142, 229, 262, 418, 449, 469, 520 and 668. Examples are the area underlain by glacial tills in the areas Drenthe and Overijssel (uc 262) as well as the peat areas. In these area drainage resistances vary strongly with depth. When the groundwater levels vary and rise or fall into a different layer, the response will be strongly non-linear. For example, when the level enters a layer with less resistance, the further increase level will be less steep as relatively much water is drained. This occurs in areas with high drainage intensities such as polders. When the ground water level enters layer with lower resistance, further rise of the ground water level will be steeper assuming the same ground water recharge. Examples for such conditions are dunes and sandy ridges.

Summarising, the analysis shows that only at a few types of sites estimates of changes in mean spring groundwater (MSGL) levels can be obtained using a linear combination of results obtained for individual changes in variables. This can be investigated by analysis of the form of the drainage function. Where this drainage function is close to a straight line over different drainage systems (layers) interpolation is possible. In other cases, scenarios have to be analysed using the MOZART-LIGHT version. Table 6.3 shows the results for the change in MSGL for the different plots assuming different P, E and EP scenarios.

Table 6.3 Results for the change in MSGL for the different plots assuming different P, E and EP scenarios. x = linear relation, - = non linear, o = linear for part of the changes.

Codes		UC-description		linear relation			change in MSGL (cm) for extreme scenarios					
UC-code	plotnr	UC-regio	UC-hydrotype	msgl	mlgl	mhgl	e-10	e+20	p-10	p20	ep-10	ep20
30	46853	Reclaimed lakes	Westland-DC-profile	x	-	o	1	-3	-3	5	-1	3
25	49516	Reclaimed lakes	Westland-D-profile	x	-	x	3	-65	-47	10	-6	5
65	74831	Dunes	Dune area	x	x	x	20	-35	-54	132	-36	73
80	39987	Dunes	Westland-DC-profile	-	-	o	4	-7	-8	7	-5	5
129	25033	High moorland	Singraven-brook valleys	x	o	x	5	-10	-9	10	-4	7
142	11796	High moorland	Westland-DH-profile	-	-	o	1	-2	-2	4	-1	2
229	75607	Fenland	Westland-DHC-profile	-	-	-	2	-2	-2	5	-1	3
222	31655	Fenland	Westland-DH-profile	x	-	o	5	-13	-11	12	-3	12
262	27555	Pleistocene areas	Eem en/of keileemprofile	-	-	-	12	-30	-44	49	-28	30
287	35613	Pleistocene areas	Open profile	x	-	o	6	-14	-27	28	-12	23
387	90646	River areas	Westland-C-profile	x	o	x	1	-1	-2	3	-1	2
418	66554	River areas	Westland-H-profile	x	o	o	0	-1	-1	1	0	1
449	54110	Sandy ridges	Keileem profile	-	-	x	1	-4	-3	4	-2	2
469	84392	Sandy ridges	Sandy ridges	o	o	x	2	-2	-9	14	-6	12
520	76458	Sandy areas	Betuwe-stroomruggronden	-	-	-	2	-3	-7	6	-4	3
577	23388	Sandy areas	Peeloo profile	-	x	-	1	-5	-4	5	-1	2
582	111698	Sandy areas	Singraven-brook valleys	-	o	o	1	-3	-5	7	-4	4
608	133605	Sandy areas	Westland-D-profile	x	o	-	2	-3	-3	5	-2	3
668	113307	Sea clay areas	Tegelen/Kedichem profile	-	o	x	1	-3	-3	6	-2	3
697	131453	Sea clay areas	Westland-DH-profile	x	o	o	2	-4	-5	8	-2	4

It should be realised that particularly in the polder areas in the Netherlands where water levels are almost completely regulated, the results for drainage and changes in ground water levels can be strongly affected by changes in management style.

7 Conclusions

In this section we will draw conclusions from the sensitivity analysis that refer to the following issues:

- Limitations of environmental change for which the models can be used
- Type of changes and measures that can be analysed directly by changing model variables and parameters. (e.g. from literature values and/or climate change scenarios)
- Type of changes and measures that can be analysed indirectly by changing variables and parameters. (by expert judgement of model developers and literature values)
- Type of changes and measures that can be analysed only indirectly by changing output variables (by expert judgement of model developers and literature values)
- Type of changes and measures that cannot be analysed
- Changes that can be estimated by linear inter- or extrapolation from reference scenarios or by means of a linear combination of the individual results obtained for single changes in input variables.

7.1 Limitations of environmental change for which the models can be used

Basin model

The limits for which RHINEFLOW-2 can be used are estimated as:
- Annual temperature change: 0 - + 5 degrees Celsius
- Annual precipitation change: -20 - +50 %
- Evapotranspiration change:
  - Direct effects: -30 - +30%
  - Indirect effects: function of temperature

These limitations are based on expert judgement. As the RHINEFLOW-2 model is partly based on empirical relations, the use of the model far outside the observed range of present day climate cannot be recommended. The ranges above are within the range observed.

IJsselmeer models

The IJsselmeer models that simulate lake levels are based on an open water balance model. Such a model is a good representation of reality. This means that there are practically no limitations on the scenarios for which the model can be applied, unless water levels will rise above the current crest levels of the surrounding dikes.

The IJsselmeer models that are used for the estimation of the crest levels are based statistical relations between wind speed, direction and lake levels etc. These relations are based on present-day conditions and the statistics will change when the climate changes. Changes between 0-20% in maximum wind speed, can be reliably simulated.

The Netherlands terrestrial area models

The limitations of the terrestrial area models are approximately the same as for the RHINEFLOW model:

- Annual temperature change: 0 - + 5 degrees Celsius
- Annual precipitation change: -20 - +50 %
- Evapotranspiration change: -30 - +30%

Also these limitations are based on expert judgement. We found no physical limitations of the terrestrial area model so far. Limitations are mainly determined by the input variables which are based on empirical relations (crop factor) and the schematisation (land use, soil type, surface levels). These boundary conditions are based on the current climate and hydrological situation in the Netherlands. The estimation of the upper limit for temperature is related to the believe that at higher temperatures crops that are not common today in the Netherlands might be cultivated. Also, a change in groundwater recharge of more than 0.4 mm/day may lead to unreliable results in certain parts of the Netherlands. This approximately coincides with a change of 30% of the net precipitation (precipitation minus evaporation). Examples of situations where the current boundary conditions might be exceeded are situations with an extreme excess of water, like:

- situation where water levels exceed the surface level in areas with a fixed surface water levels are not maintained at a certain level,
- situation with excessive amounts of drainage may result in a total drainage from storage canals and catchment areas to main canals which are physical not possible,
- situation where groundwater levels reach the surface level and additional precipitation has to lead to inundation have yet not been modelled. In theory these situations can be simulated, however, the models have not been validated for such conditions.

Furthermore, events such as individual heavy rain storms, occurring within the used ten-day time-step will be smoothed over ten-days. Experiments are being carried out for modelling with a day as time-step. Taking all these aspects into account gives to the above mentioned limitation of the terrestrial models.

7.2 Type of changes and measures that can be analysed directly by changing model variables and parameters

Basin model

With the RHINEFLOW-2 model the following changes can be analysed directly:

- Changes in temperature;
- Changes in precipitation;
- Changes in evapotranspiration;
- Changes in the water balance due to changes in land use.

IJsselmeer models

With the models available in WINBOS the following changes can be analysed directly:

- Changes in River Rhine/IJssel discharge;
- Change in sea level;
- Change in precipitation;
- Change in evaporation;
- Changes in water management / target levels;
- Change discharge capacity discharge sluices;
- Change in pumping capacity.

Terrestrial models

The following measures can be analysed by adaptation of input variables and/or parameters using NAGROM-MONA-MOZART:

- Changes in precipitation;
- Changes in evaporation;
- Changes in land use on evapotranspiration;
- Change (reallocation or limitation) of drinking and industry water use;
- Changes sprinkling water use;
- Changes in target water levels used by the water management.

The following types of measures can be analysed using the Distribution Model:

- Changes in priorities in the availability of water for different users;
- Different management style;
- Management surface water levels of lakes (IJsselmeer, Randmeren, stuwpanden Maas). This affects the capture of water from the lakes;
- Restricting the withdrawal of water with a capacity (for example pumping-engine) and possibilities of water supply.

7.3 Type of changes and measures that can be analysed indirectly by changing model variables and parameters

Basin model

The following changes can be analysed indirectly using the RHINEFLOW model:
- Changes in separation coefficient due to changes in land use;
- Changes in direct effects of CO_2 on water use efficiency of crops by changes in the crop coefficient.

The following measures can be analysed indirectly by further modifying output of the RHINEFLOW-2 model:

- Changes in operation rules for lakes and reservoirs;
- Changes in the channel/infrastructure.

IJsselmeer models

In the WINBOS instrument the wind speed can not be changed. Scenario's assuming different wind statistics have to be outside WINBOS.

- Effect of changing wind speed on crest height

The Netherlands terrestrial areas models

The following changes can be modelled by NAGROM-MOZART-MONA by changing an input parameter with expert judgement:

- Changes in direct effects of CO_2 on transpiration (expert judgement on crop factor);
- Land subsidence (by changing drainage and surface levels);
- Reduction in land subsidence (expert judgement on adjusting drainage levels only when a certain drainage depth (reclamation) is reached);
- Changes in drainage intensity;
- Water management styles by expert judgement on changing drainage regulation rules.
- Flooding of polders by adjusting surface water level to boezem-level;
- Disconnecting sewer system by changing recharge in urban areas;

7.4 Inter- and extrapolation of reference scenarios and linear combinations

Basin models

- The response of the annual runoff on temperature rise is nearly linear. However the sensitivity of annual runoff to temperature rise is small. Within the year, discharge response is not linear as differences occur between the winter and the summer period (snowfall).
- The response of the annual runoff to precipitation increase varies from year to year. A wet year will show a stronger increase than a dry year. This means that the response is not linear.
- The response of evaporation on changes in water use efficiency of crops is simulated in the same manner as shifts in crop type. Both lead to linear changes in evaporation. Such changes can easily be derived from each other.

The sensitivity of the models used is such that combined changes will not lead to an (unexpectable) exponential hydrological response. However, combined changes cannot be easily derived from each other, as the response might be non-linear.

Summarising, it will be necessary to evaluate nearly all scenarios individually by the basin models. However, as these models do not require a lot of computing time, this can be done without much effort.

The IJsselmeer models

- The rise of the average maximum lake levels in the IJsselmeer and Randmeren rise is close to the sea level rise. This means that different scenarios can be obtained by interpolation.
- Wind effects are large on the design crest heights of the surrounding dikes. These effects cannot be estimated from interpolation of scenarios.
- Both average summer and winter water levels cannot be derived by interpolation from reference scenarios. Large differences exist between the Randmeren, the Markermeer and the IJsselmeer.

The sensitivity of the models used is such that combined changes will not lead to an (unexpectable) exponential hydrological response. However, combined changes cannot be easily derived from each other, as the response might be non-linear.

Summarising this means that to obtain a complete analysis of the effects of climate changes on the IJsselmeer scenarios will have to be computed separately. Only the effects on average maximum levels can be derived directly from the sea level rise.

The Terrestrial models

The Mean Spring Groundwater Level is expected to respond linearly to precipitation or evaporation change within the range evaluated reclaimed lakes and sandy areas. The linear relation holds when the changes of the groundwater level stay within one layer (primary, secondary or tertiary system) of the drainage regulation function or in plots where for the different layers nearly the same drainage resistances are assumed.

On the other hand there are areas where the local geo-hydrological conditions result in a strongly non-linear response. Examples are the area underlain by glacial tills in the areas Drenthe and Overijssel, peat areas, polders and dunes and sandy ridges. In these areas the drainage resistance varies strongly with depth. When the groundwater levels vary and rise or fall into a different layer, the response will be strongly non-linear.

The analysis using the MOZART-LIGHT model shows that only at a few types of sites estimates of changes in groundwater levels can be obtained using a linear combination of results obtained for individual changes in variables.

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