Effects of climate and land-use change on lowland stream ecosystems

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ABSTRACT

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During the past decades human interference in regional hydrologic systems has intensified. These systems act as an integrating medium. They link climate, human activities and ecological processes through groundwater and surface water interactions. In this study we have examined the potential impacts of climate and land-use change on the streams Beerze and Reusel in the Netherlands.

For examining the potential impacts of climate change we have followed a scheme involving predictions for:

- indirect effects of climate change, that are transferred to ecological subsystems through the regional hydrologic system
- direct effects of climate change, through the direct influence of temperature on the growth and reproduction of plant species, and the dispersal of aquatic invertebrates

Large effects on peak discharges are predicted for some of the climate scenarios. Effects on terrestrial ecosystems are moderate and mainly positive. Under all scenarios the climate change had a significantly negative effect on the stream community of the aquatic ecosystem.

Key words: climate change, hydrology, ecology, ecosystem, stream, lowland

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Contents

PREFACE

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SUMMARY

During the past decades human interference in regional hydrologic systems has intensified. These systems act as an integrating medium. They link climate, human activities and ecological processes through groundwater and surface water interactions. In this study we have examined the potential impacts of climate and land-use change on the streams Beerze and Reusel in the Netherlands.

For examining the potential impacts of climate change we have followed a scheme involving predictions for:

- indirect effects of climate change, that are transferred to ecological subsystems through the regional hydrologic system
- direct effects of climate change, through the direct influence of temperature on the growth and reproduction of plant species, and the dispersal of aquatic invertebrates

The results for the study region indicate a high sensitivity of the peak discharges to the precipitation: an increase of the winter precipitation by 17% causes a more than 50% increase of peak discharges. A third of that effect is due to the specific statistical structure of the precipitation series in the climate scenario. The remaining two-thirds is due to the nonlinear response of the catchment.

The watertables in stream valleys are well stabilized by upward seepage of groundwater. Compared to the impact of other human influences like agricultural drainage, the effects of climate change on the area of wet and moist riverine grasslands in stream valleys are moderate, and mostly they are positive. The positive effect is caused by the increased winter

precipitation on the watertables and by the positive effect of extra evapotranspiration: the higher evapotranspiration draws extra seepage into the root zone. The latter process is important for the pH-buffering. The extra evapotranspiration is not enough to cause moisture stress in the stream valleys.

Under all scenarios the climate change had a significantly negative effect on the stream community of the aquatic ecosystem. The direct effect of temperature rise on the aquatic community is expected to be large. Species now seen in for instance the northern half of France are expected to appear in the Netherlands if the expected temperature rise indeed takes place. This migration of species is also predicted for the stream valley vegetation.

EXECUTIVE SUMMARY

Introduction

During the past decades human interference in regional hydrologic systems has intensified. These systems act as an integrating medium, linking climate, human activities and ecological processes through groundwater and surface water interactions. For more than a decade now the 'desiccation' of the Dutch rural areas has been the subject of many studies. This desiccation is for instance caused by the artificial drainage of agricultural lands. Of more recent date is the interest in the potential impacts of climate change. In this study we have examined these potential impacts and also the possible interactions with land-use change.

For studying the potential impacts of climate change we have followed a scheme involving predictions for:

- indirect effects of climate change, that are transferred to ecological subsystems through the regional hydrologic system
- direct effects of climate change, through the direct influence of temperature

The objective of the study was in the first place to develop a methodology for predicting the effects of climate change, and for being able to predict the interaction with land and water use measures like removal of artificial drainage. A study region was used to provide feedback for the methodological work and to give an example of the results that the methodology can produce. This study region is the Beerze and Reusel drainage basin in the south of the Netherlands, with an area of about 45 000 ha.

Scenarios

For the climate scenarios we used a weather series generated for 2070-2100 by the General Circulation Model (GCM) of the Hadley Centre for Climate Prediction and Research. The mean temperature of this weather series shows a 2.8 ^{o}C rise compared to the current climate (1980-1998). In the Hadley scenario the long-term mean of the precipitation does not differ much from the current climate. In order to do justice to the uncertainties with respect to the the future climate, we decided to also include scenarios involving a 6% increase of the winter precipitation per ^{o}C rise of mean temperature. This 'rule-of-thumb' has been advocated by the Dutch Royal Meteorological Institute, KNMI. For the 2.8^{o}C rise of temperature this means an

Table S.1 List of scenarios. The code names of the scenarios have two components. The first component indicates the land and water use scenario, the second the climate scenario.

Scenario code	Land and water use	Climate scenario
Cur_His	Current situation	Historic precipitation for six regional gauging stations
Cur_HisPa	Current situation	Regionally averaged historic precipitation
Cur_Had	Current situation	Downscaled Hadley weather series for 2070-2100
Cur_HadPi	Current situation	Downscaled Hadley weather series, KNMI rule-of-thumb (17% increase of winter precipitation, 3% increase of summer precipitation)
Cur_HadEr	Current situation	Downscaled Hadley weather series, reduced evapotranspiration due to reduced crop factors
Cur_HadPiEr	Current situation	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation, reduced evapotranspiration
Ehs_His	Implemented ecological network Ehs	Historic precipitation
Ehs_HadPi	Implemented ecological network Ehs	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation
EhsBuf_His	Ehs, buffer zone of extensive grassland	Historic precipitation
EhsBuf_Had	Ehs, buffer zone of extensive grassland	Downscaled Hadley weather series
EhsBuf_HadPi	Ehs, buffer zone of extensive grassland	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation
EhsBuf_HadEr	Ehs, buffer zone of extensive grassland	Downscaled Hadley weather series, reduced evapotranspiration
EhsBuf_HadPiEr	Ehs, buffer zone of extensive grassland	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation, reduced evapotranspiration
EhsBufM_His	Ehs, buffer zone, free meandering of main streams	Historic precipitation
EhsBufM_Had	Ehs, buffer zone, free meandering of main streams	Downscaled Hadley weather series
EhsBufM_HadPi	Ehs, buffer zone, free meandering of main streams	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation

increase of the winter precipitation by 17%. We have also taken into consideration that there is uncertainty about the future crop evapotranspiration in view of the expected doubling of CO_2-concentration in the atmosphere. For climate we have investigated a total of five scenarios: the current climate and four possible alternatives for the future (Table S.1). So instead of attempting to make real predictions, we have made a number of ‘what-if’ analyses.

Apart from the influence of climate we have also investigated the interaction with several land and water use scenarios. These scenarios involved the implementation of the so-called National Ecological Network (series *Ehs* in Table S.1), of protection zones (also called ‘buffer zones’) around the stream valleys involving extensification of agriculture (series *EhsBuf*), and free meandering of the main streams (series *EhsBufM*).

Regional hydrology and stream morphology

For simulating the regional hydrology the integrated model SIMGRO has been used. SIMGRO is a comprehensive model of soil water, groundwater and surface water. For groundwater the simulations are made with a time-step of 0.25 d; for surface water the time step is only 0.025 d in order to simulate the highly dynamic behavior of the water level under wet conditions. For very wet conditions in the stream valleys the precipitation falling on fully saturated soils is simulated as becoming rapid runoff. The model was set up for the study region using data available in various databases. The calibration was performed in a systematic and reproducible manner. The ‘goodness of fit’ was measured with quantitative criteria for both watertables and surface water discharges.

For the stream morphology a method was set up that can predict the equilibrium dimensions of the stream if left to freely meander. It also yields results for the sinuosity of the stream, which is the distance along the meandering stream itself divided by the distance along the stream valley ('as the crow flies'). The method makes use of the bank-full discharge simulated by SIMGRO. The bank-full discharge is a discharge that has a recurrence interval of 1.6 years.

For coupling to ecological models several procedures for post-processing of SIMGRO have been developed:

- a downscaling method for giving the watertable with a resolution of a 25 x 25 m grid
- an algorithm for estimating the upward seepage to the root zone in nature areas

- a simple groundwater quality model for estimating the calcium saturation of deep seepage that reaches the root zone; the deep seepage is enriched by calcium through contact with calciferous sediments
- an algorithm for computing the moisture stress of natural vegetation
- a calculation method for discharge-extremity intervals for effects on aquatic ecology

Aquatic ecology of lowland streams

A stream is a dynamic but balanced environment. Macro-invertebrates are seen as indicator species, and are therefore used for predicting the impacts of climate change. These effects on lowland stream aquatic ecosystems were investigated by means of a field study in ten streams. All streams were near-natural but differed in discharge regimes and substrate patterns. It appeared that discharge–substratum types are not simple and predictable, and neither do they show simple linear relationships with macro-invertebrate distribution.

The major macro-invertebrate distribution appeared to be explained by substrates at the habitat scale. Furthermore, at the scale of the stream a gradient from flashy streams towards constantly discharging streams added to the explanation. This gradient is partly affected by substrate and partly by other environmental conditions.

In general, most indicative macro-invertebrates show preferences for specific substrate types and stream velocity classes. These habitats of substrate and stream velocity occur under specific conditions that only occur in a few of the ten studied streams. Many more data on different streams with different hydrological regimes are necessary to support the development of a discharge-related preference indication tool based on macro-invertebrates. Still, as discharge dynamics were the most important hydrological characteristic affecting macro-invertebrate distribution at the stream level, this parameter was used for the development of an ecologically relevant discharge dynamics index (DDI). The ecological relevance of the discharge dynamics index was tested against four biological metrics. It was concluded that the biological metrics support the DDI as a measure of hydrological quality in the studied streams.

Terrestrial ecology of lowland streams

For estimating the effects of changes in hydrology on lowland stream terrestrial ecosystems the NATLES model has been used. On the basis of hydrology, type of soil, and land use it predicts the site conditions and ecosystem type in a new equilibrium situation. Relevant site conditions in this study are moisture regime, acidity and nutrient availability. ‘Moisture regime’ is a complex factor, used to indicate a complex of factors that are linked to the amount of water available. It is used to describe differences in medium (aquatic versus terrestrial systems), aeration and moisture supply. The site conditions are described in terms of discrete classes, using an ecologically relevant classification.

As to the prediction of the moisture regime some adaptations of NATLES were made for use in this study. In the first place we took into account that owing to changed climatic conditions new factor combinations might appear. Increased evapotranspiration could lead to site types with both anaerobic conditions in spring (caused by shallow watertables) and moisture stress in summer, owing to deep watertables and high evapotranspiration. Furthermore, the way the moisture stress is calculated has been altered. For present climatic conditions the moisture stress is predicted as a function of soil texture and Mean Lowest Watertable, using functions calculated with the SWAP model (a one dimensional site model of soil water – plant – atmosphere interactions). However, these functions are valid for present climatic conditions only. For use in this study new functions were derived, that predict the moisture stress as a function of:

- the number of days that the watertable is below a critical level for upward capillary transport
- the cumulative precipitation deficit

Calculation of the moisture stress takes place outside the NATLES model itself, as a post-processing of the SIMGRO results.

Ecosystem types can be distinguished on the basis of vegetation structure and site conditions. For presentation purposes in the study use has been made of an aggregated ecosystem classification. Ecosystem types that are most relevant in this study because of their high nature conservation value are ‘wet and very moist riverine grasslands’, characterized by shallow spring watertables, low to medium nutrient availabilities, and moderately acidic to basic conditions. In the present climatic conditions they are characterized by vegetations belonging to the *Junco-Molinion* and *Calthion palustris* types.

Effects on regional hydrology and stream morphology

It appears that the peak discharges of streams are highly sensitive to precipitation. In scenario *Cur_HadPi* with winter precipitation increased by 17% both of the investigated streams Beerze and Reusel reacted with peak discharges that are >50% higher than under the current climatic conditions. So the increase of winter precipitation is amplified by a factor three in the increase of peak discharges. About one third of this effect is caused by the specific statistical structure of the precipitation series in the climate scenario. In terms of the parameter that is known to determine the peak discharge – the 10-day moving average rainfall – the effect on the discharge is not treble but *double* the precipitation increase. The underlying cause for the 'doubled' reaction to the increased winter precipitation is to a large part the increase of very wet areas along the stream-valley bottoms. When they become saturated these areas generate rapid runoff. Also field ditches and drains become more active. It is not clear how representative the >50% response is for other streams in the Netherlands.

In the scenarios with reduced crop factors (*Cur_HadEr* and *Cur_HadPiEr,* see Table S.1) the reduced evapotranspiration means less lowering of watertables at the end of summer, meaning that the build-up of shallow watertables during the winter period has a 'wetter' starting point. The reduced evapotranspiration adds an additional 7% to the computed peak discharges.

The investigated land and water use scenarios do not appear to have much influence on the peak discharges. Even the free meandering of streams with a shallowing of the stream cross-section does not seem to have much effect. The expected increase of peak discharges due to the shallowing of watertables does not occur because of the increased sinuosity of the stream: The latter makes the stream more sluggish, and the stream itself becomes more of a bottle-neck in the discharge process.

In the stream valleys the upward seepage to the root zone essential for the terrestrial ecology appears to be sensitive to the climate change. In scenario *Cur_Had* (the driest scenario), for instance, there is a 34% increase of the area with an upward seepage higher than the ecologically critical level of 0.5 mm/d. Here the evapotranspiration plays a dominant role (the extra evapotranspiration sucks the seepage into the rootzone); the sensitivity to the winter precipitation is much less due to the cancelling-out of countereffects (more upward seepage, but also a thicker precipitation lense). The effects of climate change on the seepage to the root zone are attenuated in the case that free meandering of streams is allowed.

For simulating the effects on the peak discharges the integration between groundwater and surface water models is essential. For simulating effects on the upward seepage to the root zone, the integration between soil water and groundwater models is essential. This stresses the point that effects of climate change can only be simulated with a regional model like SIMGRO that has a tight integration between all components of the regional hydrological system.

Effects on aquatic ecology

The discharge dynamics index DDI was calculated for the sixteen scenarios of Table S.1. The average DDI-scores differed significantly for most of the scenarios in comparison to the reference (current climate condition), even though the numerical value of the average index only differed slightly. The scenarios all showed a decrease of the index score. Under all scenarios the climate change had a significantly negative effect on the stream community. Also looking at the sites which dry up for a longer period of time it appeared that all scenarios showed an extended number of desiccated sites. Desiccation is fatal for most stream communities.

Comparing the current climate condition with the implemented National Ecological Network (scenario series *Ehs*), with the scenarios having buffer zones of extensive grassland (series *EhsBuf*), and with the scenarios having free meandering main streams (series *EhsBufM*), it is concluded that none of these additional measures influenced the discharge dynamics index very much. This does not mean that especially the additional measures will not affect the macro-invertebrate community. On the contrary these measures will have an ecological effect but these effects are not included in the hydrological quality assessment.

The direct effects of climate change were evaluated through the use of stream temperature. Stream temperature is very important for the distribution of stream macro-invertebrates. Under the hypothesis that stream temperature will increase by about 3 ^{o}C in 2100, the temperature regime in the Netherlands will become similar to the one that we now have in the northern half of France. The study showed that the groups of *Tricladida*, *Hydracarina*, *Plecoptera*, *Odonata*, *Coleoptera* and *Heteroptera* will profit. Their number of species will increase in the Netherlands. The numbers of *Orthocladiinae* and *Oligochaeta*, on the other hand, will decrease.

Effects on terrestrial ecology

Compared to the impact of other human influences like agricultural drainage, the effects of climate change on the area of wet and moist riverine grasslands are moderate, and mostly they are positive. In the scenarios *Cur_HadPi* and *Cur_HadPiEr* the increased precipitation leads to higher groundwater levels. In the scenarios *Cur_Had* and *Cur_HadPi* with increased evapotranspiration (as a consequence of increased temperature and radiation in the Hadley weather series for 2070-2100), the increased evapotranspiration increases the area under the influence of upward seepage. The latter is an important factor for pH buffering. Both changes lead to an increase in the area of wet and moist riverine grasslands. A possible negative effect is that due to higher summer evapotranspiration the groundwater fluctuations will increase. However, in the studied scenarios the groundwater fluctuations in wet and very moist riverine grasslands are not large enough to create conditions with significant moisture stress.

By contrast, in the higher infiltration areas the climate scenarios lead to much more pronounced effects on the relative areas of ecosystem types. In scenario *Cur_Had* (the driest scenario) the relative area of dry heathland strongly increases, whereas in scenario *Cur_HadPiEr* (the wettest scenario) the increased precipitation leads to a marked shift from dry to moist heathland.

To assess possible changes in the floristic composition of wet and moist riverine grasslands due to increased temperature, a comparison was made with similar ecosystems in a region with temperatures more or less the same as predicted for the Netherlands. The Sologne and the Brenne area in France appeared to be best suited for this purpose. A comparison with the types of vegetation occurring there in wet and moist riverine grasslands shows that these types of vegetation are floristically often very similar to the Dutch *Junco-Molinion* and *Calthion palustris*. This especially holds for the stands on mineral-rich alluvial soils with *Calthion palustris* (Dutch classification) and *Oenantho-Brometum* (French classification), which are also most similar in abiotic conditions. Nevertheless, there are also obvious floristic differences that are coupled to differences in climate, such as the occurrence of a number of umbelliferous species with a more southern distribution in the *Oenantho-Brometum* stands. With increasing temperatures the distribution range of these species will move in a more northerly direction. On the other hand in the Dutch *Calthion-palustris* vegetation types the number of *Carex* species is much larger than in the French riverine grasslands, and it is likely that some of these species will disappear or become rare as a result of climate change.

Another observation was that *Caricion nigrae* vegetation types, which in the Netherlands are characteristic for sites with superficial acidification due to the stagnation of rainwater, were absent in the reference area. Furthermore, peat soils are completely lacking. This can be explained by the fact that deeper watertables and higher temperatures promote the breakdown of organic matter.

With regard to the rather optimistic expectations for changes in wet and moist riverine grasslands a reservation must be made for the fact that the effects of flooding were not incorporated in our model. In the wetter scenario an increase in the area of wet and moist riverine grasslands like *Junco-Molinion* and *Calthio* types is predicted. However, if the water quality of the Beerze and Reusel rivers does not improve, the increased flooding with eutrophic water might actually result in a decrease of these target ecosystem types and an increase in less wanted types of vegetation with species such as *Glyceria fluitans* and *G. maxima*.

NEDERLANDSE SAMENVATTING

Inleiding

In de afgelopen 50 jaar zijn de antropogene invloeden op regionale hydrologische systemen geïntensiveerd. Deze systemen hebben een integrerende functie, die klimaat, menselijke activiteiten en ecologische processen met elkaar verbinden via grond- en oppervlaktewater interacties. Sinds de tachtiger jaren is de ‘verdroging’ van landelijke gebieden intensief bestudeerd. Deze verdroging wordt onder meer veroorzaakt door aanleg van landbouwkundige drainage. Van meer recente datum is de belangstelling voor potentiële effecten van klimaatverandering en de mogelijke versterking van effecten die met verdroging samenhangen.

Voor het bestuderen van potentiële effecten van klimaatverandering is een schema gevolgd met onderscheid tussen:

- indirecte effecten van klimaatverandering ten gevolge van effecten die via het hydrologische systeem worden overgebracht
- directe effecten van klimaatverandering als gevolg van temperatuursinvloeden

Het doel van de studie was in de eerste plaats het ontwikkelen van een methodologie voor het voorspellen van effecten van klimaatverandering, en voor het voorspellen van de wisselwerking van klimaatverandering met land- en watergebruiksmaatregelen zoals het aanleggen van landbouwkundige drainage. Een concreet studiegebied is gebruikt voor het toetsen van de methodologie en om een voorbeeld te hebben voor het geven van mogelijke uitkomsten. Het studiegebied van 45 000 ha betreft het stroomgebied van de Beerze en Reusel in de Provincie Noord-Brabant.

Scenarios

Voor de klimaatscenarios is gebruik gemaakt van de weerreeks voor 2070-2100 die is gegenereerd door het *General Circulation Model* (GCM) van het *Hadley Centre for Climate Prediction and Research* in Engeland. De gemiddelde dagtemperatuur van de weerreeks is 2,8 ^{o}C hoger dan de huidige waarde voor het studiegebied. Het langjarig gemiddelde van de neerslag wijkt echter niet veel af van de huidige situatie. Omdat temperatuurwijziging mogelijk ook leidt tot een toename van de neerslag is besloten om ook scenarios door te

Tabel S.1 Lijst van scenarios. De codes voor de scenarios bestaan uit twee componenten die gescheiden worden door een '_'-teken. De eerste component geeft het land- en watergebruik aan, de tweede component het klimaatscenario

Scenario code	Land- en watergebruik	Klimaatscenario
Cur_His	Huidige situatie	Gemeten neerslag voor zes regionale stations
Cur_HisPa	Huidige situatie	Regionaal gemiddelde van gemeten neerslag
Cur_Had	Huidige situatie	Neergeschaalde Hadley weerreeks voor 2070-2100
Cur_HadPi	Huidige situatie	Neergeschaalde Hadley weerreeks, KNMI vuistregel (17% toename van de winterneerslag, 3% toename van de zomerneerslag)
Cur_HadEr	Huidige situatie	Neergeschaalde Hadley weerreeks, verminderde verdamping door verlaagde gewasfactoren
Cur_HadPiEr	Huidige situatie	Neergeschaalde Hadley weerreeks, KNMI vuistregel voor de neerslag, verminderde verdamping door verlaagde gewasfactoren
Ehs_His	Geïmplementeerde EHS (Ecologische Hoofdstructuur)	Gemeten neerslag
Ehs_HadPi	Geïmplementeerde EHS	Neergeschaalde Hadley weerreeks, KNMI vuistregel voor de neerslag,
EhsBuf_His	Geïmplementeerde EHS, bufferzone extensief grasland	Gemeten neerslag
EhsBuf_Had	Geïmplementeerde EHS, bufferzone extensief grasland	Neergeschaalde Hadley weerreeks
EhsBuf_HadPi	Geïmplementeerde EHS, bufferzone extensief grasland	Neergeschaalde Hadley weerreeks, KNMI vuistregel voor de neerslag
EhsBuf_HadEr	Geïmplementeerde EHS, bufferzone extensief grasland	Neergeschaalde Hadley weerreeks, verminderde verdamping door verlaagde gewasfactoren
EhsBuf_HadPiEr	Geïmplementeerde EHS, bufferzone extensief grasland	Neergeschaalde Hadley weerreeks, KNMI vuistregel voor de neerslag, verminderde verdamping door verlaagde gewasfactoren
EhsBufM_His	Geïmplementeerde EHS, bufferzone extensief grasland, vrije meandering hoofdbeken	Gemeten neerslag
EhsBufM_Had	Geïmplementeerde EHS, bufferzone extensief grasland, vrije meandering hoofdbeken	Neergeschaalde Hadley weerreeks
EhsBufM_HadPi	Geïmplementeerde EHS, bufferzone extensief grasland, vrije meandering hoofdbeken	Neergeschaalde Hadley weerreeks, KNMI vuistregel voor de neerslag

rekenen waarbij de winterneerslag met 6% per ^{o}C temperatuurstijging is verhoogd, volgens de bekende vuistregel van het KNMI die in veel studies wordt toegepast. Voor de 2,8 ^{o}C stijging van temperatuur komt dat neer op een 17%-stijging van de winterneerslag. Er is ook rekening gehouden met de onzekerheid ten aanzien van de toekomstige gewasverdamping in verband met de voorspelde verdubbeling van de CO_2-concentratie in de atmosfeer. Voor het klimaat hebben we derhalve in totaal vijf scenarios onderzocht: het huidige klimaat en vier mogelijke combinaties van neerslag- en verdampingvarianten (Tabel S.1). Gezien de onzekerheid met betrekking tot het toekomstige klimaat heeft de study de vorm aangenomen van een serie 'als-dan' analyses.

Behalve de invloed van het klimaat hebben we ook de wisselwerking met meerdere land- en watergebruikscenarios bekeken. Deze scenarios betroffen de implementatie van de Ecologische Hoofdstructuur, de EHS (serie *Ehs* in Tabel S.1), van bufferzones rondom de beekdalen waarbij tot een afstand van 1 km alle grondgebruik wordt omgezet naar extensief grasland (serie *EhsBuf*), en het vrij meanderen van de hoofdbeken (serie *EhsBufM*).

Regionale hydrologie en beekmorfologie

Voor het simuleren van de regionale hydrologie wordt gebruik gemaakt van het regionale model SIMGRO. SIMGRO is een geïntegreerd model van bodem-, grond- en oppervlaktewater. Het grondwater wordt gesimuleerd met een tijdstap van 0,25 dag. Voor het oppervlaktewater wordt een tijdstap van slechts 0,025 dag gebruikt, om het dynamische gedrag goed te beschrijven. Bij zeer natte omstandigheden in de beekdalen wordt de neerslag die op de volledig verzadigde bodem valt afgevoerd als oppervlakkige afstroming. Het model is opgezet op basis van data uit diverse basisbestanden. De kalibratie van het model is systematisch aangepakt en goed vastgelegd. Bij de beoordeling van de voorspelling van het waargenomen systeemgedrag is gebruik gemaakt van kwantitatieve criteria voor zowel de grondwaterstanden als de beekafvoer.

Voor de beekmorfologie is een berekeningsmethode opgezet die kan voorspellen wat het evenwichtsprofiel van de beek zal zijn als de beek wordt vrijgelaten om zich op een natuurlijke manier te ontwikkelen. Voorspellingen worden gedaan voor het dwarsprofiel en voor de zogenaamde sinuositeit, die een maat is voor het meandergedrag: de sinuositeit is de lengte langs de beek gedeeld door de lengte langs de dalbodem. De gebruikte sleutelparameter voor het maken van de voorspelling is de zogenaamde *bank-full discharge*, dat is de afvoer die zich gemiddeld eens per 1,6 jaar voordoet. In de natuurlijke situatie wordt het dwarsprofiel dan tot aan de rand gevuld.

Voor het koppelen van het hydrologische model met de ecologische modellen zijn de volgende procedures ontwikkeld:

- een neerschalingsmethode voor het voorspellen van grondwaterstanden in gridcellen van 25 x 25 m
- een algoritme voor het voorspellen van de ecologisch relevante kwel naar de wortelzone
- een eenvoudig grondwaterkwaliteitsmodel voor het voorspellen van de calciumconcentratie van de kwel naar de wortelzone; calcium wordt in oplossing gebracht door contact met kalkhoudende gesteenten in de diepe ondergrond
- een algoritme voor het berekenen van de droogtestress van de natuurlijke vegetatie
- een methode voor het bepalen van de extreme afvoeren ten behoeve van aquatisch-ecologische voorspellingen

Stromend water ecologie

De indirecte effecten van klimaatsveranderingen op beekecosystemen zijn onderzocht aan de hand van een gedetailleerde studie in tien laaglandbeken. Het betrof nagenoeg natuurlijke boven- en middenlopen, die verspreid over Nederland zijn gelegen en onderling slechts verschilden in afvoerpatroon en in substraatvariatie. Deze afvoer-substraat relaties bleken nauwelijks aan elkaar gerelateerd noch bleek de macrofaunasamenstelling hiermee in direct verband te staan.

Op het niveau van het beekhabitat echter bleek de macrofauna door de substraten te worden verklaard. Terwijl op beekniveau de macrofaunaverspreiding door de afvoerdynamiek bleek te worden (mede)bepaald. De tien beken zijn te ordenen langs een gradiënt van beken met een sterk wisselende afvoer enerzijds versus beken met een zeer constante afvoer anderzijds. Een tweede gradiënt, die afwijkingen van beken ten opzichte van de eerste gradiënt bepaalde, werd veroorzaakt door substraatverschillen.

Op soortsniveau zijn groepen macrofauna te onderscheiden die duidelijke preferenties voor verschillende substraattypen en stroomsnelheidsklassen vertoonden. De soorten bleken in hun verspreiding naast deze specifieke habitatpreferenties vaak in hun verspreiding ook beperkt te zijn tot enkele beken. Voor het bepalen van afvoerdynamiek-preferenties is daarom een grotere hoeveelheid basisgegevens noodzakelijk. Onze tien beken blijken daarvoor ontoereikend te zijn.

Desondanks is getracht om de afvoerdynamiek te vertalen in een ecologisch relevante en bruikbare parameter, omdat deze factor toch de belangrijkste verklarende factor was in de onderzochte beken. Hiertoe is de afvoerdynamiek-index (DDI) geformuleerd. De ecologische relevantie van de DDI is bepaald door de scores van de index in de tien onderzochte beken te toetsen tegen vier ecologische indices gebaseerd op de aanwezige macrofauna. Drie van de vier ecologische indices ondersteunden de DDI als maat voor de hydrologische kwaliteit van de tien beken. De DDI is daarom ingezet om de ecologische effecten van klimaatsveranderingen te voorspellen.

Terrestrische ecologie

Om de effecten van de hydrologische veranderingen op terrestrische vegetaties te kunnen voorspellen is gebruik gemaakt van het model NATLES. Dit model bepaalt op grond van invoergegevens over bodemtype, hydrologie en beheer de standplaatscondities en het ecosysteemtype in een nieuwe evenwichtssituatie. De standplaatscondities die worden voorspeld zijn voedselrijkdom, zuurgraad en vochttoestand. De laatste term wordt gebruikt om een complex van factoren aan te duiden die te maken hebben met de aanwezigheid van water, te weten het medium waarin de planten leven (aquatische versus terrestrische systemen), de aëratie en de vochtvoorziening. De standplaatscondities worden beschreven in termen van discrete klassen, uitgaande van een klasse-indeling op basis van voor de plantengroei relevante grenzen.

Voor deze studie zijn in NATLES een aantal veranderingen doorgevoerd in de manier waarop de vochttoestand wordt bepaald. In de vochtindeling is er rekening mee gehouden dat de klimaatsveranderingen kunnen leiden tot nieuwe combinaties van factoren. Door de toegenomen verdamping kunnen standplaatsen ontstaan waar zowel anaërobe omstandigheden optreden, door hoge grondwaterstanden aan het begin van het groeiseizoen, als perioden met droogtestress als het gevolg van toegenomen verdamping en lagere grondwaterstanden later in het seizoen. Verder is de wijze van berekening van de droogtestress aangepast. Voor het huidige klimaat wordt de droogtestress (aantal dagen dat een vochtspanning van –12 m in de wortelzone wordt onderschreden) bepaald als een functie van de bodemtextuur en de GLG (Gemiddeld Laagste Grondwaterstand), gebruik makend van functies die zijn berekend met het model SWAP (een eendimensionaal standplaatsmodel van bodemwater-plant-atmosfeer interacties). Deze functies zijn echter alleen bruikbaar voor de huidige klimaatomstandigheden. Daarom zijn nieuwe functies afgeleid, waarin de droogtestress wordt gegeven als een functie van:

- het aantal dagen dat de kritische grondwaterstand wordt onderschreden
- het maximaal optredende cumulatieve verdampingstekort in een jaar

Op basis van vegetatiestructuur en standplaatscondities kunnen ecosysteemtypen worden onderscheiden. Voor de weergave van effecten is in deze studie uitgegaan van een vereenvoudigde ecosysteemindeling. Meest van belang vanwege hun hoge natuurwaarde zijn de natte en zeer vochtige beekdalgraslanden, die worden gekenmerkt door hoge voorjaarsgrondwaterstanden, een geringe tot matige voedselrijkdom en matig zure tot basische condities. In het huidige klimaat worden deze ecosystemen gekarakteriseerd door vegetaties die behoren tot het *Junco-Molinion* en het *Calthion palustris*.

Effecten op de hydrologie en beekmorfologie

Uit de rekenresultaten blijkt dat de gesimuleerde piekafvoeren zeer gevoelig zijn voor de winterneerslag. In scenario *Cur_HadPi* met een winterneerslag die 17% hoger is dan in de huidige situatie, neemt de maatgevende afvoer van zowel de Beerze als de Reusel toe met meer dan 50%. De toename van de winterneerslag wordt dus drie maal versterkt in de berekende toenames van maatgevende afvoeren. Ongeveer eenderde van dat effect wordt veroorzaakt door de afwijkende statistische structuur van de opeenvolging van neerslaggebeurtenissen in het klimaatscenario. Gezien in termen van de parameter die de piekafvoer feitelijk bepaalt – de 10-daagse neerslagsom – is het effect op de piekafvoer niet drie keer, maar *twee* keer de neerslagtoename. De onderliggende oorzaak van deze ‘dubbele’ toename betreft vooral de toename van de zeer natte zones langs de beekdalen. Als deze zones volledig verzadigd raken genereren zij oppervlakkige afstroming. Ook andere ontwateringsmiddelen worden meer actief als de vullingsgraad van de ondergrond toeneemt. Maar het is niet duidelijk in hoeverre de berekende effecten representatief zijn voor andere beken in Nederland.

In de scenarios met lagere gewasfactoren (*Cur_HadEr* en *Cur_HadPiEr)* blijkt dat de verminderde verdamping nog een extra effect heeft op de piekafvoeren: er wordt nog eens 7% aan het effect van de neerslag toegevoegd. Het extra effect wordt veroorzaakt door het minder ver wegzakken van de grondwaterstanden in het najaar. Daardoor is er een ‘natter’ beginpunt voor de opbouw van hoge grondwaterstanden in het winterhalfjaar.

De onderzochte land- en watergebruikscenarios lijken niet veel invloed te hebben op de gesimuleerde piekafvoeren. Zelfs het vrij meanderen van beken en de bijbehorende versmalling van dwarsprofielen heeft weinig effect. Dat de verwachte toename van piekafvoeren niet plaatsvindt komt doordat de invloed van de nattere beekdalen wordt gecompenseerd door de langere afgelegde afstand van het water in de meanders. Daardoor neemt het verhang van de waterspiegel af, en wordt de beek trager.

In de beekdalen blijkt de berekende hoeveelheid kwel naar de wortelzone van natuurlijke vegetaties sterk beïnvloed te worden door veranderingen van klimaat. In scenario *Cur_Had* bijvoorbeeld (het droogste scenario), neemt het areaal met >0.5 mm/d kwel toe met ca. 34%. Vooral toename van de verdamping geeft een toename van de kwel naar de wortelzone (de kwel wordt door de extra verdamping als het ware de wortelzone ingezogen). Het effect van de neerslag op de kwel naar de wortelzone is veel kleiner, als gevolg van het elkaar neutraliseren van tegeneffecten (meer kweldruk, maar ook een dikkere neerslaglens). De effecten van klimaatverandering worden gedempt als vrije meandering van beken wordt toegestaan.

Voor het simuleren van effecten op de piekafvoeren is de integratie van modellen voor grond- en oppervlaktewater essentieel. Voor het simuleren van de kwel naar de wortelzone is de integratie tussen modellen voor bodem- en grondwater juist onmisbaar. Het is dus gebleken hoe belangrijk het is om gebruik te maken van een geïntegreerd model zoals SIMGRO voor het voorspellen van effecten van klimaatveranderingen op beekecosystemen.

Effecten op stromend water ecologie

De afvoerdynamiek-index DDI is berekend voor de zestien klimaat- en landgebruikscenarios van Tabel S.1. De DDI-scores bleken in veel gevallen significant te verschillen van de hydrologie onder het huidige klimaat. Met andere woorden uit alle klimaatscenarios bleek een significant effect op de beekdynamiek en daarmee op het beekecosysteem. Voor alle scenarios bleek de DDI af te nemen, hetgeen betekent dat de hydro-ecologische toestand in de Nederlandse laaglandbeken als gevolg van klimaatsveranderingen zal verslechteren. Ook bleek dat het aantal droogvallende beekbovenlopen in de toekomst zal toenemen; met andere woorden klimaatsveranderingen gaan de effecten van verdroging versterken. Verdroging is desastreus voor aquatische levensgemeenschappen.

Additionele maatregelen zoals het implementeren van de EHS, het aanleggen van bufferzones en het hermeanderen van beken leiden niet tot verbetering van de hydrologische kwaliteit. Dit betekent weliswaar niet dat deze maatregelen geen ecologische verbetering bewerkstelligen, integendeel zelfs. Maar deze zeker verwachte verbetering is niet nader onderzocht of meegewogen.

De directe effecten van klimaatsverandering zijn onderzocht op basis van de factor temperatuur. Voor de beekwatertemperatuur is voor het jaar 2100 uitgegaan van een temperatuurstijging van circa 3 °C. Dit is een temperatuursregime dat momenteel zich manifesteert in delen van Noord-Frankrijk. Het onderzoek heeft aangetoond dat onder dit temperatuursregime het aantal macrofaunasoorten uit de groepen platwormen, watermijten, steenvliegen, libellen, waterkevers en waterwantsen zal toenemen. Hier tegenover staat een verwachte afname van het aantal soorten van de vedermuggen en de weinig borsteldragende wormen. Over het geheel zal de biodiversiteit, uitgedrukt in het aantal soorten, toenemen.

Effecten op terrestrische ecosystemen

De veranderingen in de oppervlakte aan natte en vochtige beekdalgraslanden als gevolg van klimaatsveranderingen is beperkt, en is in de meeste scenarios bovendien positief. In de scenarios *Cur_HadPi* en *Cur_HadPiEr* leidt de toegenomen neerslag tot hogere voorjaars-grondwaterstanden, en in de scenarios *Cur_Had* en *Cur_HadPi* leidt de toegenomen verdamping (als een gevolg van stijgende temperaturen en toegenomen straling) tot meer kwel naar de wortelzone. Beide veranderingen leiden tot een uitbreiding van het areaal natte en zeer vochtige beekdalgraslanden. Een mogelijk negatief effect is dat door de toegenomen verdamping de grondwaterstandfluctuaties toenemen. In de onderzochte klimaatscenarios is echter geen sprake van een zodanige toename van de fluctuaties in natte en zeer vochtige beekdalgraslanden dat droogtestress te verwachten is.

In de hoger gelegen infiltratiegebieden is de gevoeligheid voor klimaatsveranderingen aanzienlijk groter. In scenario *Cur_Had* (met toegenomen verdamping, het droogste scenario) neemt het relatieve aandeel droge heide sterk toe, terwijl in scenario *Cur_HadPiEr* (met toegenomen neerslag en afgenomen gewasfactoren, het natste scenario) er een aanzienlijke verschuiving plaatsvindt van droge naar vochtige heide.

Om een indruk te krijgen van mogelijke veranderingen in floristische samenstelling van de beekdalgraslanden als gevolg van temperatuurveranderingen is een vergelijking uitgevoerd met een referentiegebied in Frankrijk. In dat gebied komen qua standplaatscondities en beheer vergelijkbare graslanden voor onder klimatologische omstandigheden zoals die in Nederland kunnen gaan ontstaan in de scenarios zonder toegenomen neerslag. De vergelijking laat zien dat de in het referentiegebied voorkomende natte graslanden qua soortensamenstelling vaak zeer vergelijkbaar zijn met de Nederlandse *Junco-Molinion* en *Calthion palustris*-vegetaties. Dit geldt met name voor de op mineraalrijke beekdalgronden voorkomende Nederlandse *Calthion palustris*-vegetaties en de Franse *Oenantho-Brometum*-vegetaties, waarvan ook de standplaatsen in hydrologie en bodemopbouw het meest op elkaar lijken. Er zijn ook een aantal duidelijke verschillen die zijn gerelateerd aan klimaatsverschillen, zoals het voorkomen van een aantal umbelliferen met een zuidelijke verspreiding in de *Oenantho-brometum*-vegetaties. Bij een stijging van de temperatuur is de verwachting dat het areaal van deze soorten naar het noorden zal opschuiven. In de Nederlandse beekdalgraslanden is het aandeel van zegge-soorten weer veel groter, en het is waarschijnlijk dat sommige van deze soorten zullen achteruitgaan of verdwijnen als gevolg van temperatuurstijging.

Opvallend is het ontbreken in het referentiegebied van *Caricion nigrae* vegetaties, die in Nederland kenmerkend zijn voor plekken met oppervlakkige stagnatie van regenwater. Ook ontbreken veengronden. Dat laatste kan worden verklaard uit de hogere temperaturen en de lagere grondwaterstanden, die de afbraak van organisch materiaal bevorderen.

Ten aanzien van de voorspelde veranderingen in de oppervlakte aan natte en vochtige beekdalgraslanden moet het voorbehoud worden gemaakt dat in de studie geen rekening is gehouden met de effecten van overstroming.

1 INTRODUCTION

1.1 Background

During the past decades human interference in regional hydrologic systems has intensified. These systems act as an integrating medium, linking various human activities and ecological processes through groundwater and surface water interactions. In this context we are interested in those interactions that are also influenced by climatic factors. An example is the lowering of watertables that has been caused by artificial drainage. Activities that have lowered watertables have also reduced the amount of calcium-rich upward seepage in stream valleys.

Both aquatic and terrestrial lowland stream ecosystems have been affected by these impacts on the regional hydrology, effects on stream morphology often forming the link between water quantity effects and ecological ones. In aquatic lowland stream ecosystems some typical macro-invertebrates and fishes are already extinct or are heavily threatened in their existence. In many places stream valley ecosystems that are dependent on high watertables in combination with calcium-rich upward seepage are suffering from desiccation and acidification, leading to domination by common species.

If left uncontrolled, current developments will no doubt lead to further degradation of regional hydrologic systems and their dependent functions. Regional authorities are therefore attempting to take measures aimed at achieving a sustainable economic development, and where possible restoring ecological systems to a more natural state. Large sums are being invested in the Dutch Nature Policy Plan. In this plan stream ecosystems form an essential link in the National Ecological Network. Climate change is a wildcard that perhaps could frustrate the attempts of regional authorities to achieve their goals.

Climate change is likely to have both direct and indirect effects on stream valley vegetation. Temperature has a direct effect on the growth and reproduction of plant species. Species that reach the limit of their distribution area in the Netherlands are extra vulnerable to climate change. Indirect effects are caused through changes of seepage, hydrodynamics and geodynamics. A similar distinction between direct and indirect effects can be made for aquatic stream ecosystems.

1.2 Objectives and scope of the study

The main objective of the study was to develop a methodology for investigating the vulnerability of lowland stream ecosystems that are subjected to climate change and other man-made influences. The methodology should not only predict effects of climate change for the current land and water use situation, but also for situations where the basin has been partly restored to a near-natural state. In other words, the methodology should also make predictions for the *ecological potential* of a basin. In fact, this became the main focus of the study. And thus the current eutrophicated status that affects nearly all drainage basins in the Netherlands has been left out of consideration. It has been assumed that in the long run this eutrophication will diminish drastically.

We studied the potential impacts of climate change using a scheme with predictions for:
- indirect effects of climate change, that are transferred to ecological subsystems through the regional hydrologic system
- direct effects of climate change, through the direct influence of temperature on the growth and reproduction of plant species, and the dispersal of aquatic invertebrates

The objective of the hydrological research was to adapt a catchment-scale integrated model of groundwater, surface water, soil water, and atmospheric interactions so that it became suitable for investigating the potential impacts of climate change. A special procedure was needed for predicting effects on the stream morphology. Special procedures were also needed for bridging the gap between the regional scale of the hydrological modelling and the local scale that is needed for making ecological effect evaluations.

The objective of the aquatic ecological research was to describe the relationships between discharge regimes, stream velocities, substrate distribution, substrate stability, and macro-invertebrate assemblages in small lowland streams. Macro-invertebrates are seen as indicator species, and therefore they are used for making the predictions.

The objective of the terrestrial ecological research was to predict effects on vegetation in stream valley grasslands. The research efforts were to result in (1) the definition of key factors and threshold values in both climate and hydrology which are relevant to vegetation development and (2) a biogeographical framework which evaluates major changes in the floristic composition of the 'goal eco-types' within the pilot area, focussing on stream valley vegetation, and

As already stated above, the primary objective of the study was to develop a methodology for predicting effects of climate change. Although the methods developed are generally applicable, the results produced for the study region can not be generalized for the whole of the Netherlands. But as we shall see in the concluding chapter it is possible to make some generalizations after all.

1.3 Study region

The study region is located in the Province of North Brabant in the southern half of the Netherlands (Figure 1.1). An overview of the Beerze-Reusel drainage basin itself is given in Figure 1.2. The subsoil mainly consists of sandy deposits formed in the Pleistocene. The region gently slopes in a north to northeast direction, from an altitude of 45 m+NAP (m above Mean Sea Level) down to 3.7 m+NAP. There are several low aeolian sand ridges several meters high that are orientated in a west to east direction. These ridges have a large impact on the geomorphology of the stream valleys, as they are situated transversely to the

Figure 1.1 Location of the study region in the southern half of the Netherlands.

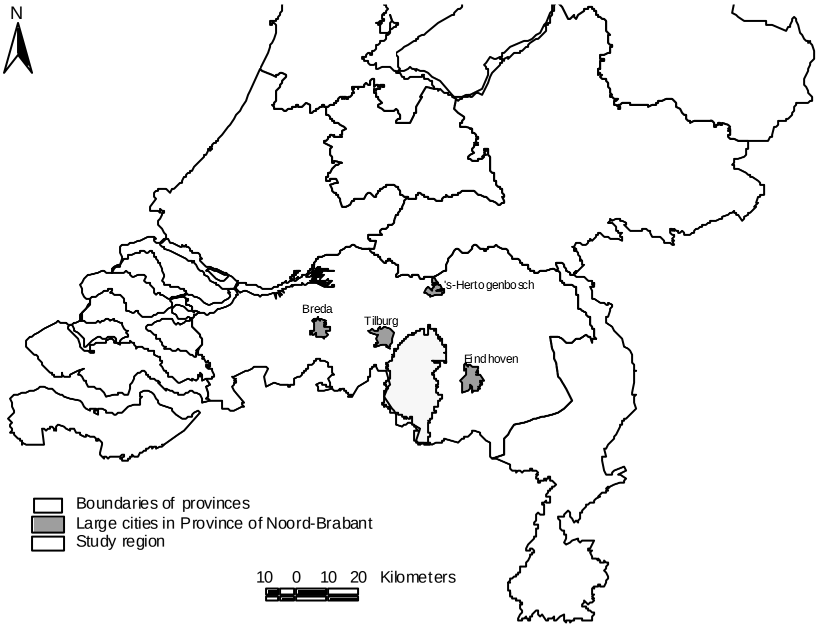
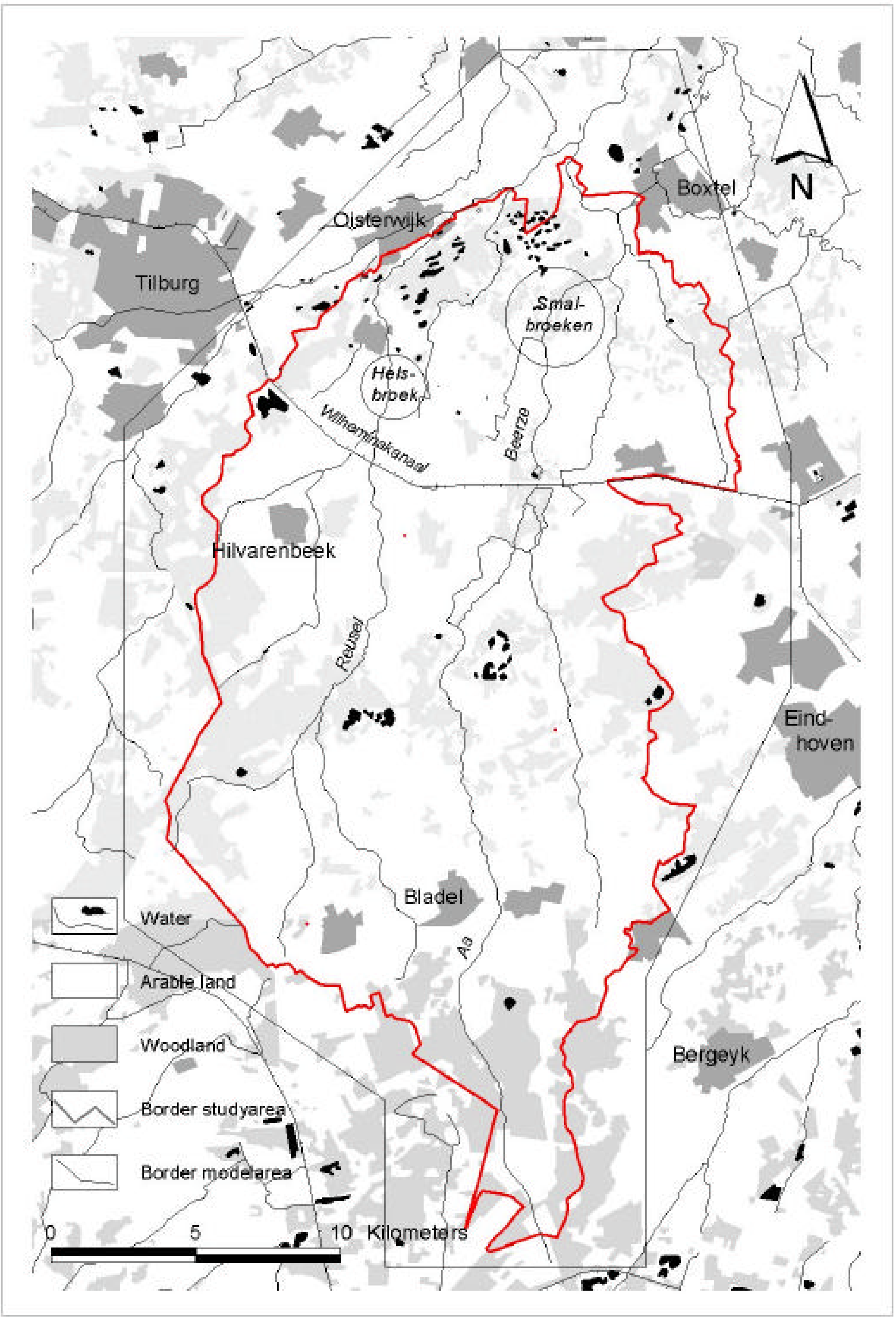


Figure 1.2 Topographic outline of the study region.



general slope and drainage pattern of the area. In those areas where the rivers traverse the sand ridges the valleys are narrow, sometimes no more than a few tens of meters. In the plains between the ridges the valleys are much wider. In the valleys alluvial soils have been formed consisting of redeposited sand, loam and peat. Because of the intensive agricultural drainage of the areas these peaty soils are strongly oxidized and have often have become very shallow.

Agriculture is the dominant land use in the region; most of the area is used for grassland and maize. In the region there are a few larger nature conservation areas of more than 1000 ha. These are mainly situated on the higher aeolian sand ridges and consist of heathland and pine plantations. The nature conservation areas in the river valleys are less numerous and are generally much smaller, sometimes not bigger than a few ha.

In this study two river valley locations have been studied in more detail (Figure 1.2). The Smalbroeken area is a nature reserve located in a place where the Beerze transects the sand ridge of the Kampina heathland. Therefore the river valley is narrow and to both sides distinctly bordered by higher sandy soils. The Helsbroek area is located just south of the place where the Reusel traverses the same aeolian sand ridge. Here the valley is rather wide, but only a small part of the valley has been kept as a nature conservation area. The two sites are representative for the two types of river valleys, and, although strongly influenced by man, are among the best-kept river valley locations in this part of the Netherlands.

1.4 Organization of the report

We start by giving a description of the climate and land use scenarios in chapter 2. Then we proceed by giving descriptions of the abiotic aspects, i.e. the regional hydrology (chapter 3) and related stream morphology (chapter 4). In chapter 5 we describe the methods for coupling hydrological to ecological models. Then in chapters 6 and 7 we describe the aquatic and terrestrial ecological systems. Only after these more generic type descriptions of the involved systems have been given do we proceed to give the predicted effects of climate change in chapters 8, 9 and 10. The description of the ecological effects is done according to the distinction given in Section 1.2 involving so-called indirect (chapter 9) and direct effects (chapter 10). In chapter 11 we make some concluding remarks.

2 CLIMATE AND LAND-USE SCENARIOS

P.E.V. van Walsum

2.1 Climate scenarios

2.1.1 Introduction

It is a fact of life for climate research that there is a great deal of uncertainty about possible climate changes that are taking place right now and/or that will take place in the future. Uncertainty about the possible changes inevitably has lead to a great diversity in the approaches for generating climate scenarios. If such diversity would also prevail within the Dutch National Research Programme (NRP) it would lead to difficulties when interpreting results of individual projects in a broader context, and would thus undermine the integration phase of the research program. For this reason the NRP has commissioned the Hadley Centre for Climate Prediction and Research to provide them with a climate scenario for European weather in the period 1980-2100 (Viner and Hulme 1998, Verweij and Viner 2001). This scenario has been generated by Hadley's general circulation model with a grid cell size of 3.75 degrees in longitude and 2.5 degrees in latitude. We have used the data for 2070-2100, because from the point of view of climate change, that is the most extreme case available.

Before proceeding to discuss the climate scenarios in detail, a list of them is given in Table 2.1. The first two scenarios pertain to the current climate conditions, and the other four are variations on the scenario supplied by the Hadley Centre. By investigating these four variations we hope to do justice to the uncertainties with respect to future conditions. Thus we do not make any real predictions, but perform analyses in a 'what-if' manner.

Table 2.1 List of climate scenarios

Scenario code	Description
His	Measured regional data for 1984-1998, precipitation series of six regional stations
HisPa	Measured regional data for 1984-1998, averaged precipitation series
Had	Downscaled and calibrated Hadley weather series for the period 2070-2100
HadPi	Downscaled and calibrated Hadley weather series for the period 2070-2100, increased precipitation according to KNMI rule-of-thumb
HadEr	*Had*, with reduced crop factors
HadPiEr	*HadPi*, with reduced crop factors

2.1.2 Current climate (precipitation)

According to the official data reports of the KNMI there is a significant east-west gradient of the mean annual precipitation in the study region. This can be concluded from the statistics of the six regional rain-gauging stations in the study region. The most easterly station reports an annual mean of 850 mm/yr for the period 1980-1998, whereas the most westerly station reports a mean of 750 mm/yr, at hardly 20 km distance. Though this difference seems highly improbable in view of the absence of significant orographic effects, it is not contradicted by the comparison between simulated and measured mean flows (see Section 3.3). The regional differences should be kept in mind when comparing results for climate scenarios with those for the current climate. It turns out that the average yearly precipitation on the Beerze drainage basin is 1.5% less than the average of the regional stations, whereas that of the Reusel basin is 5% more. For making a proper analysis the scenario with the *averaged* precipitation plays an important role, with the average taken of the six rain-gauging stations on a daily basis. Therefore it has been included as *HisPa* in the scenario list of Table 2.1. The current climate is included under the code name *His.*

For the current climate (*His* and *HisPa*) the data of the period 1984-1998 were used instead of the 1980-1998-period that was used in the calibration of the downscaling of the Hadley series described in the next section (2.1.3). The reason is that 1984-1998 reflects better the average climatological conditions in terms of the simulated groundwater regime, as was concluded from a simulation run with the meteorological data of De Bilt for 1969-1999. For the six regional stations the data availability was limited to 1980-1998. In terms of the average annual precipitation the period 1980-1990 (794 mm/yr) only differs slightly from 1984-1998 (790 mm/yr).

2.1.3 Downscaled Hadley weather series

For the Netherlands – and for the drainage basin of Beerze and Reusel in particular – the best-centered grid cell of the Hadley GCM is not the most suitable one. The reason is that the grid cell has a substantial part of its area over the North Sea, and therefore it has a too moderate temperature regime. So we have chosen a grid cell that lies more to the north-east. It is more northerly than the study region, but it does have roughly the same distance to the coast. The latter circumstance is considered to be of more importance than the Northern Latitude. The chosen grid cell (Eastern Longitude between 5.625^o and 9.375^o, Northern Latitude between 51.25^o and 53.75^o) has its center at roughly the same Northern Latitude as Amsterdam, and lies about 50 km east of the eastern border. The most westerly boundary of the cell cuts through the center of the Netherlands.

The Hadley weather variables used for this study are daily values of: precipitation (mm/d), temperature (^{o}C), relative humidity (%), and total downward surface short-wave flux (W/m^2/d). In Table 2.2 a comparison is made between the long-term means of the weather variables for the Hadley grid cell and the means of measured weather variables for the study region. This comparison for the period 1980-98 shows that there are significant differences. These differences have to be somehow reconciled, otherwise the use of the Hadley weather series for predicting effects of *future* climate would also include effects of differences for the *current* climate. The effects caused by the latter would be an artefact. To avoid this the Hadley weather series has first been downscaled to the study region, and only then used for predicting effects of climate change.

Table 2.2 Comparison between long-term means of Hadley weather series and the means of measured variables for the study region of Beerze and Reusel, for the period 1980-1998.

Weather variables	Beerze & Reusel	Hadley cell
Precipitation (mm/yr)	794	746
Summer precipitation (mm/yr)	377	403
Winter precipitation (mm/yr)	417	343
Temperature (^{o}C)	9.87	9.13
Relative humidity (%)	82	88
Total downward surface SW flux (W/m/day)	113	114

For temperature, relative humidity and short-wave flux the downscaling of the Hadley series was done in the following simple manner:

- the daily temperatures of the Hadley series (1980-2100) were increased by 0.74 ^{o}C, to account for the difference between the long-term mean of 9.87 ^{o}C of the measured daily values for 1980-98 and 9.13 ^{o}C of the Hadley series
- the relative humidity and the short-wave flux were adjusted by multiplying with the ratios derived from the data in Table 2.2

Table 2.3 Long-term means of temperature, humidity and shortwave flux (SW flux). Data are given for the current climate (taken as 1980-1998) and for the selected period defining the climate scenario, 2070-2100. Explanation of symbols for series:

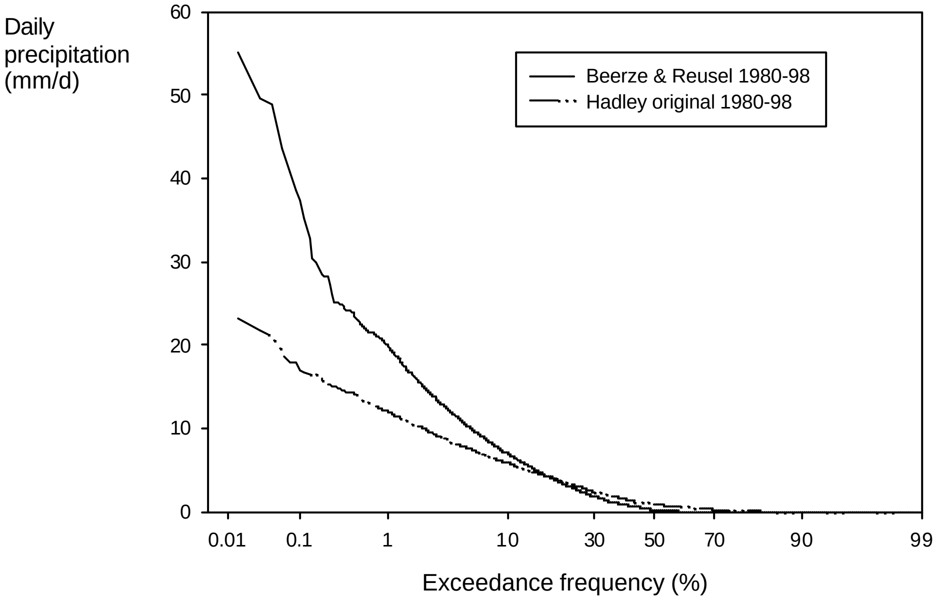
- B&R1980-98 : measured regional series
- H1980-2100 : original Hadley series for the grid cell, for 1980-1998
- H2070-2100 : original Hadley series for the grid cell, for 2070-2100
- H2070-2100C : downscaled and calibrated Hadley series, for 2070-2100

Weather variable	B&R 1980-98	H1980-98	H2070-2100	H2070-2100C
Temperature (^{o}C)	9.87	9.13	11.90	12.64
Relative humidity (%)	82	88	86	80
SW flux (W/m^{2}/d)	113	114	120	118

In our study we used the data of 2070-2100 for defining the climate scenario. The long-term means of temperature, humidity and short-wave flux are given in Table 2.3, column 'H2070-2100'.

As can be seen from the comparison of mean temperatures in Table 2.3 the period 2070-2100 has a mean temperature that is 2.8 ^{o}C higher than for the period 1980-98 (Hadley series). The mean temperature of the calibrated Hadley series (H2070-2100C) is 0.74 ^{o}C higher than the original series, as a consequence of the downscaling to the study region.

Figure 2.1 Comparison between frequency distributions of daily precipitation for the measured regional series (upper curve) and the original Hadley series for 1980-1998 (lower curve)



Downscaling of the precipitation is less straightforward. That is because not only the long-term means differ from those of the study region, but also the frequency distribution of the daily precipitation is much less skewed for the grid cell of the GCM in comparison to the measured values for the study region: In the Hadley series daily precipitation is at most 23 mm, whereas in the study area daily precipitation of up to 55 mm can occur. This difference is caused by the averaging-out of rainfall events over the large grid cells, as can be seen from the comparison of frequency distributions given in Figure 2.1.

In order to do justice to the measured daily variation of the precipitation, the precipitation of the Hadley series has to be transformed in some manner. In the literature (e.g. Wardlaw *et al*. 1996), various methods are reported for transforming GCM-rainfall data to a regional series with a realistic daily variability. These methods nearly all involve the use of stochastic weather generators like WTHGEN (Richardson 1981). The disadvantage of such methods is that the link between the original data and the calibrated ones becomes rather indirect. For this reason we have chosen a more direct approach. The method involves the following steps:

1. the precipitation data for the period 1980-1998 are ordered according to their magnitude, for both the measured regional data and the original Hadley series
2. the original Hadley data are downscaled to regional ones by using the ordered sets of precipitation data as a *lookup table*; so if for instance a daily rainfall of 10 mm in the Hadley series for 1980-1998 has the same exceedance probability as 15 mm in the measured series, then a daily precipitation of 10 mm in the 1980-2100 Hadley series is replaced by a value of 15 mm
3. long term means are computed of the transformed Hadley series and of the measured regional series, separately for winter and summer, for the period 1980-98
4. the daily values of the transformed Hadley series (1980-2100) are multiplied by the ratio between the long-term mean of the measured regional series and the transformed Hadley series for the same period as for the measurements (1980-98); this procedure is applied separately for the winter and summer period

The last step will be explained in more detail, first in more general terms and then using data of the selected period.

By calibrating to the long-term means separately for winter and summer (step 4) it is ensured that the long-term means of the transformed Hadley series are reconciled with the long-term

Table 2.4 Long-term means of precipitation. Explanation of symbols for series:
- B&R1980-98 : measured regional series
- H1980-2100 : original Hadley series for the grid cell, for 1980-1998
- H2070-2100 : original Hadley series for the grid cell, for 2070-2100
- H2070-2100C : downscaled and calibrated Hadley series, for 2070-2100
- H2070-2100CK : downscaled and calibrated Hadley series, with upward correction of precipitation based on KNMI rule-of-thumb (Section 2.1.4)

Weather variable	B&R 1980-98	H1980-98	H2070-2100	H2070-2100C	H2070-2100CK
Precipitation (mm/yr)	794	746	720	771	877
Summer prec. (mm/yr)	377	403	373	349	389
Winter prec. (mm/yr)	417	343	347	422	488

means of the measured series, for both winter and summer. That is hydrologically and ecologically important, because the dominant processes are different in the winter and summer half-year.

Comparison of the precipitation means (Table 2.4) shows that the Hadley series for 2070-2100 is only slightly different from that for 1980-1998: winter precipitation is the same, and the summer precipitation reduces by 7%. Also the frequency distributions show no significant changes (not shown).

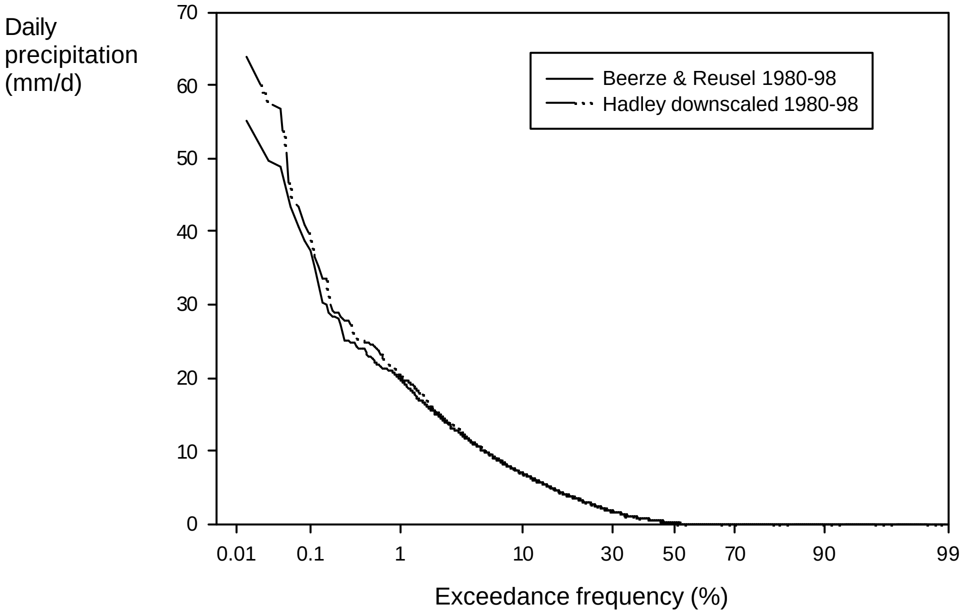
To illustrate the followed method, the relationships between some of the data shown in Table 2.4. are explained, using the summer precipitation as an example: The daily data of the transformed and calibrated series have been adjusted in such a manner that:

$$P_{summer,H2070\text{-}2100C} = P_{summer,B\&R1980\text{-}98} * (P_{summer,H2070\text{-}2100} / P_{summer,H1980\text{-}98}) \quad (2.1)$$

in which P_{summer} is the long-term mean of the summer precipitation, with the subscripts referring to the scenarios in Table 2.4. Seen in this way, the percentage increase of H2070-2100 with respect to H1980-98 – which is the predicted climate *change* – is superimposed on the current climate of the study region, thus avoiding the artefact mentioned earlier in this chapter.

The comparison between the frequency distributions of the measured regional series and the calibrated Hadley series is given in Figure 2.2 for the measurement period. The distributions

Figure 2.2 Comparison between frequency distributions of daily precipitation for the measured regional series and the calibrated Hadley series for 1980-1998.



are not quite identical due to the calibration factors for the long-term averages in summer and winter. But the significant deviations only concern the three highest precipitation events in a 19-year period, i.e. a period of 6940 days. In this context another point of consideration is that the lookup-table based on the data for 1980-98 does not cover the full range of precipitations that occur in the Hadley original series for 2070-2099: in the latter period there are two events (26.2, 25.6 mm) that are higher than the highest daily rainfall of Hadley in the period 1980-98 (23.2 mm). These two higher events are transformed to downscaled ones using the highest daily rainfall of the measured series, whereas strictly speaking they should have been translated to higher values. But since the calibration factors already cause an ‘artificial’ increase of extreme daily rainfall (Figure 2.2) it has been expedient to *not* have translated the mentioned extreme events to higher values than the top entry in the lookup-table: now the two kinds of error compensate each other.

Since the weather is a stochastic process, the most extreme events in a weather series should anyhow be treated with care when used for predictions. That is because they are subject to pure chance: if the weather series had been twice as long, the 6th highest daily precipitation would no doubt differ substantially from the 3rd highest in the series of 19 years. In our predictions of ecological effects, these events do not play a role, because they do not happen often enough to have a lasting impact on the ecological system. And as far as the peak flows are concerned, they do not occur as a consequence of single extreme events, but as a consequence of a *series* of events involving a build-up of watertables.

2.1.4 KNMI method for adjusting precipitation

In the Netherlands, extensive use has been made of a rule-of-thumb advocated by the Royal Meteorological Institute for modifying precipitation data based on changes of the mean temperature (Können *et al.* 1997). KNMI admits of course that there is great uncertainty involved.

The method actually involves corrections of daily precipitation based on the daily temperature and the change of mean temperature involved in the climate scenario. The direction of the corrections is invariably upward. Application of this method to the time series for De Bilt (located in the middle of the Netherlands) yielded the following shifts of long-term averages per ^{o}C of temperature increase:

- 1% increase of the mean summer precipitation
- 6% increase of the mean winter precipitation

In order to cover a broad range of possible scenarios, it was decided to also include a scenarios using the KNMI rule-of-thumb. Since the Hadley series for 2070-2100 involves an increase of the mean temperature by 2.8 ^{o}C, the daily values of the (calibrated) Hadley precipitation have been corrected as follows:

- 3% increase of all values in the summer
- 17% increase of all values in the winter

The long-term mean of the yearly total increases by 10%. The long-term means have been tabulated in Table 2.4 in the column ‘Hadley 2070-2099CK’

2.1.5 Influence of increased CO_2- concentration on evapotranspiration

Closely related to the future climate scenarios are the uncertainties involved in the increase of the CO_2-concentration. This increase in concentration will possibly affect the evapotranspiration through the physiology of crops. A major consideration is the possible reduction of the time that crops need for absorbing the required CO_2 through open leaf pores. The possible influences of CO_2 on crop evapotranspiration have been listed by Haasnoot *et al.* (1999). These influences have also been applied to part of the scenarios used in this study. The change of crop evapotranspiration factor is a reduction of 10% for grassland and a reduction of 36% for arable land crops. These extra scenarios complete the list given in Table 2.1.

2.1.6 Statistics of precipitation in scenarios

For being able to interpret results of scenarios it is important to know more about the time series of the precipitation data than the simple yearly and half-yearly (winter/summer) averages. A single extreme precipitation event of 1 day will generally occur in summertime, since at that time the occurrence of severe thunderstorms is most likely. Since an extreme precipitation event in summer will generally occur when the soil is relatively dried out, there will also be a lot of unused storage capacity available for soaking up the water. For the very extreme events this may not play a role, because then the system is swamped in one single day. But for the circumstances thought to be determining for the stream morphology (Section 4) events with an average recurrence interval of 1.6 years are of interest. Events with such a relatively high occurrence frequency usually occur in wintertime. And for a situation to have enough impact on the system the precipitation event must involve a ‘build-up’ period, for letting the groundwater and soil water system to become nearly saturated. For analysing the occurrence of such ‘build-up’ events it is expeditious to calculate *k-day* moving averages and

Table 2.5 Statistical parameters of precipitation series, with an average recurrence interval of 1 year

Scenario	K-day moving average (mm)				Increase (%)			
	1d	5d	10d	20d	1d	5d	10d	20d
HisPa	25	64	84	130	-	-	-	-
Had	32	61	92	132	28	-5	10	2
HadPi	36	71	106	153	44	11	26	18

Table 2.6 Statistical parameters of precipitation series, with an average recurrence interval of 10 years

Scenario	*k*-day moving average (mm)				Increase (%)			
	1d	5d	10d	20d	1d	5d	10d	20d
HisPa	52	82	104	144	-	-	-	-
Had	61	84	111	160	17	2	7	11
HadPi	70	97	129	184	35	18	24	28

analyse their statistics. In Table 2.5 and 2.6 the statistics are compared for the three scenarios that differ in terms of their precipitation series and that all involve regional averages using one single precipitation series.

2.2 Land and water use scenarios

In the Netherlands big changes are foreseen in the land and water management of the rural areas. One of the main driving forces behind these changes is the intention to form an integrated network of nature areas called the National Ecological Network. It is interesting to see whether the effects of climate change are much different when possible scenarios of land and water use are implemented. In Figure 2.3 the areas are indicated where the projected 'new nature' of the National Ecological Network are located. In the scenarios *Ehs_..* the land use has been changed to 'wet riverine grassland' in the areas where new nature will be located. In these areas all the ditches have been removed in the simulation model. It is foreseen that in

Figure 2.3 Areas that are affected in the investigated land and water use scenarios.

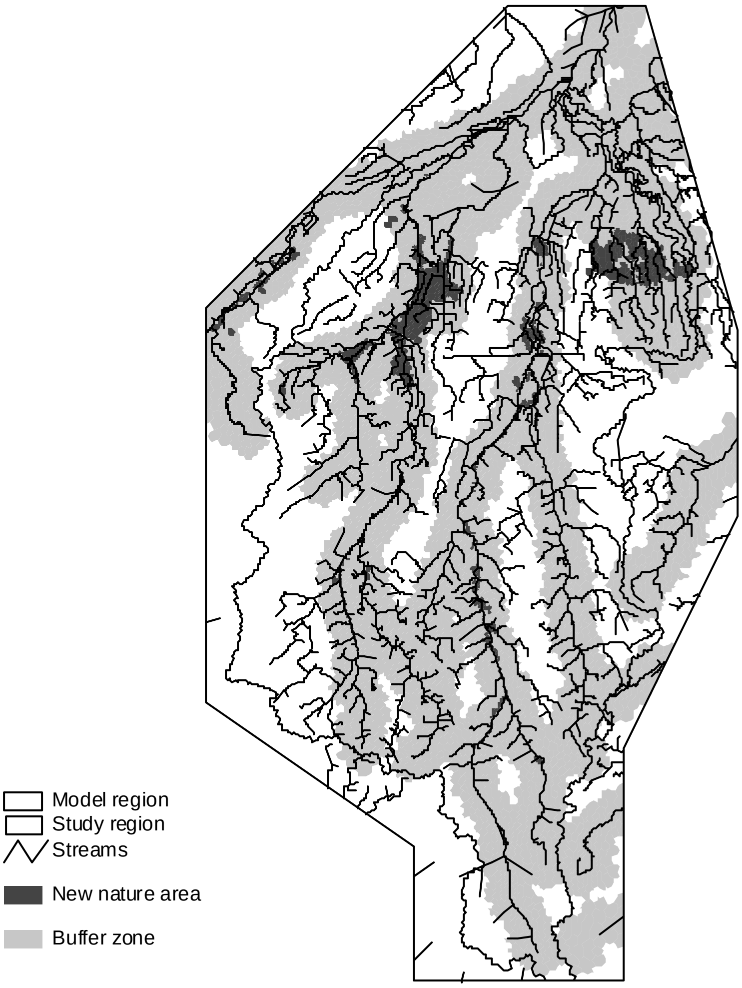


Table 2.7 List of scenarios. The code names of the scenarios have two components that are separated by an ‘_’-sign. The first component indicates the land and water use scenario, the second component the climate scenario.

Scenario code	Land and water use	Climate scenario
Cur_His	Current situation	Historic precipitation for six regional gauging stations
Cur_HisPa	Current situation	Regionally averaged historic precipitation
Cur_Had	Current situation	Downscaled Hadley weather series for 2070-2100
Cur_HadPi	Current situation	Downscaled Hadley weather series, KNMI rule-of-thumb (17% increase of winter precipitation, 3% increase of summer precipitation)
Cur_HadEr	Current situation	Downscaled Hadley weather series, reduced evapotranspiration due to reduced crop factors
Cur_HadPiEr	Current situation	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation, reduced evapotranspiration
Ehs_His	Implemented ecological network Ehs	Historic precipitation
Ehs_HadPi	Implemented ecological network Ehs	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation
EhsBuf_His	Ehs, buffer zone of extensive grassland	Historic precipitation
EhsBuf_Had	Ehs, buffer zone of extensive grassland	Downscaled Hadley weather series
EhsBuf_HadPi	Ehs, buffer zone of extensive grassland	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation
EhsBuf_HadEr	Ehs, buffer zone of extensive grassland	Downscaled Hadley weather series, reduced evapotranspiration
EhsBuf_HadPiEr	Ehs, buffer zone of extensive grassland	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation, reduced evapotranspiration
EhsBufM_His	Ehs, buffer zone, free meandering of main streams	Historic precipitation
EhsBufM_Had	Ehs, buffer zone, free meandering of main streams	Downscaled Hadley weather series
EhsBufM_HadPi	Ehs, buffer zone, free meandering of main streams	Downscaled Hadley weather series, KNMI rule-of-thumb for precipitation

the vicinity of the new nature areas additional measures will be necessary in the surrounding agricultural land. The goal of these measures is to raise watertables in the new nature areas. One way to attempt this is to marginalize the agriculture in the surrounding areas; that is what has been implemented in the simulation model for the scenarios *EhsBuf_..* :

- sprinkling has been stopped
- the agricultural drainage (if present) has been removed
- the ditches have been made less deep, to a maximum depth of 0.90 m
- the distance between the ditches has been made at least 100 m
- the land use has been set to grassland

Finally, some of the *EhsBuf*-scenarios have also been run with free meandering of the main streams. These scenarios are coded *EhsBufM_..* . Not all possible combination-scenarios have been run, because that was not considered to give extra information. A summary of all scenarios is given in Table 2.7.

3 REGIONAL HYDROLOGY

P.E.V. van Walsum, F.J.E van der Bolt, and A.A. Veldhuizen

3.1 Introduction

The focus of this study is on predicting effects involving interactions at or near the soil surface and in the waterways that form the surface water system. It is therefore a logical choice to use a regional hydrologic model of the comprehensive type, and not a model that for instance covers only groundwater. Comprehensive models that describe all aspects of the regional system in great detail have, however, the disadvantage that they are computationally very intensive and allow only the simulation of short time periods. An example of such a model is the SHE model (Abbot *et al*. 1986). When studying the impacts of climate change it is of paramount importance that long periods can be simulated, because 'climate' is defined for periods that span 20-30 years. And for coming to grips with statistics of events with a recurrence interval of for instance 5 years, it is also important to be able to simulate long enough periods. For this reason and for the fact that the model has specific options suitable for describing the special aspects of lowland hydrology, the choice was made to use the model SIMGRO (Veldhuizen *et al*., 1998). SIMGRO covers all relevant aspects of the regional hydrologic system, but does so in a manner that allows the simulation of long time periods, even for models of a mid-sized drainage basin. This has been achieved by setting integration above detail in the model conception. Figure 3.1 and Figure 3.2 give a general idea about SIMGRO and the way that it covers the regional hydrology.

We will describe various aspects of this model in more depth as we describe its implementation for the study region. For a comprehensive description of the model the reader is referred to Veldhuizen *et al*. (1998).

Figure 3.1 Schematization of water flows in SIMGRO, by means of transmission links and storage elements.

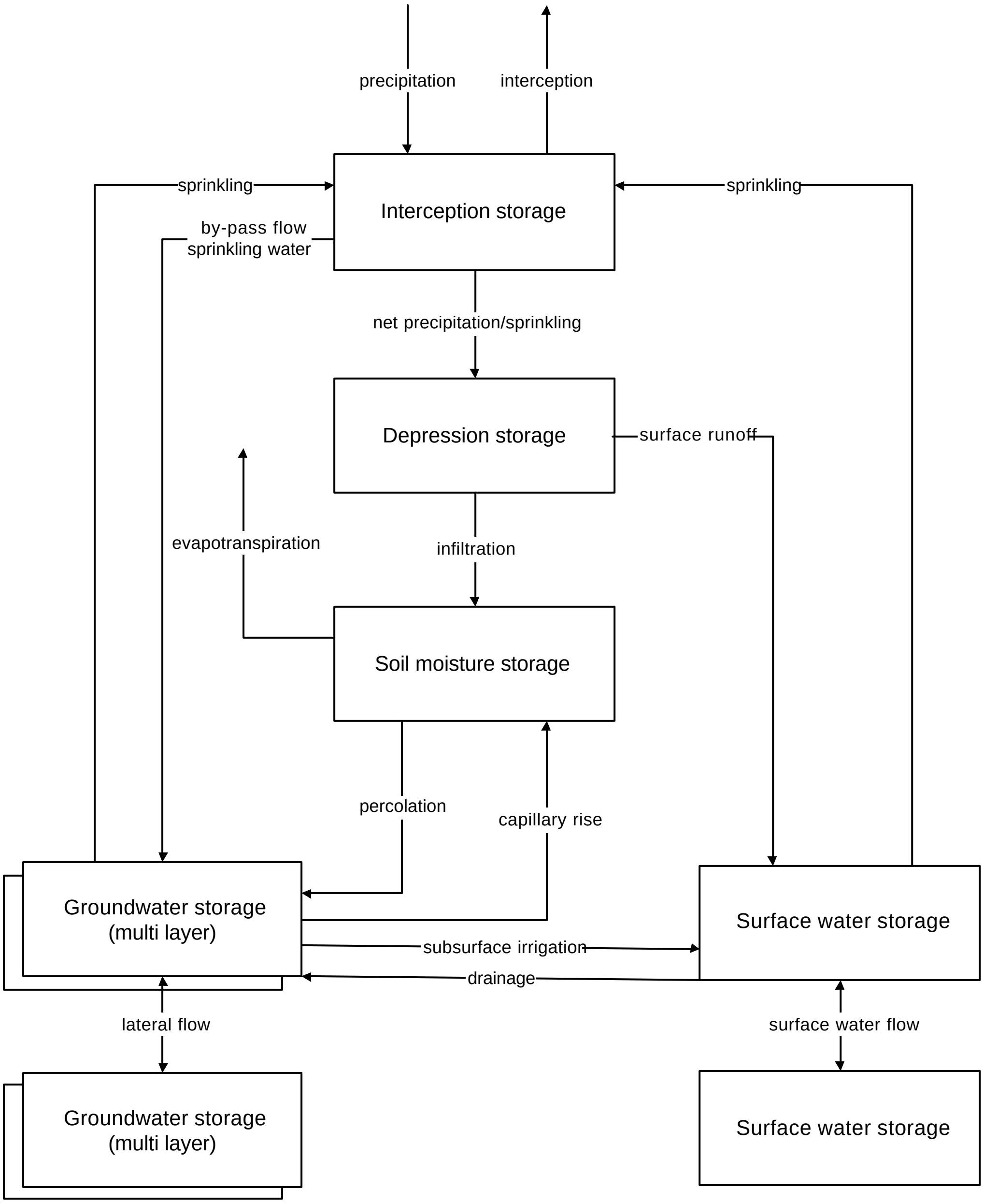
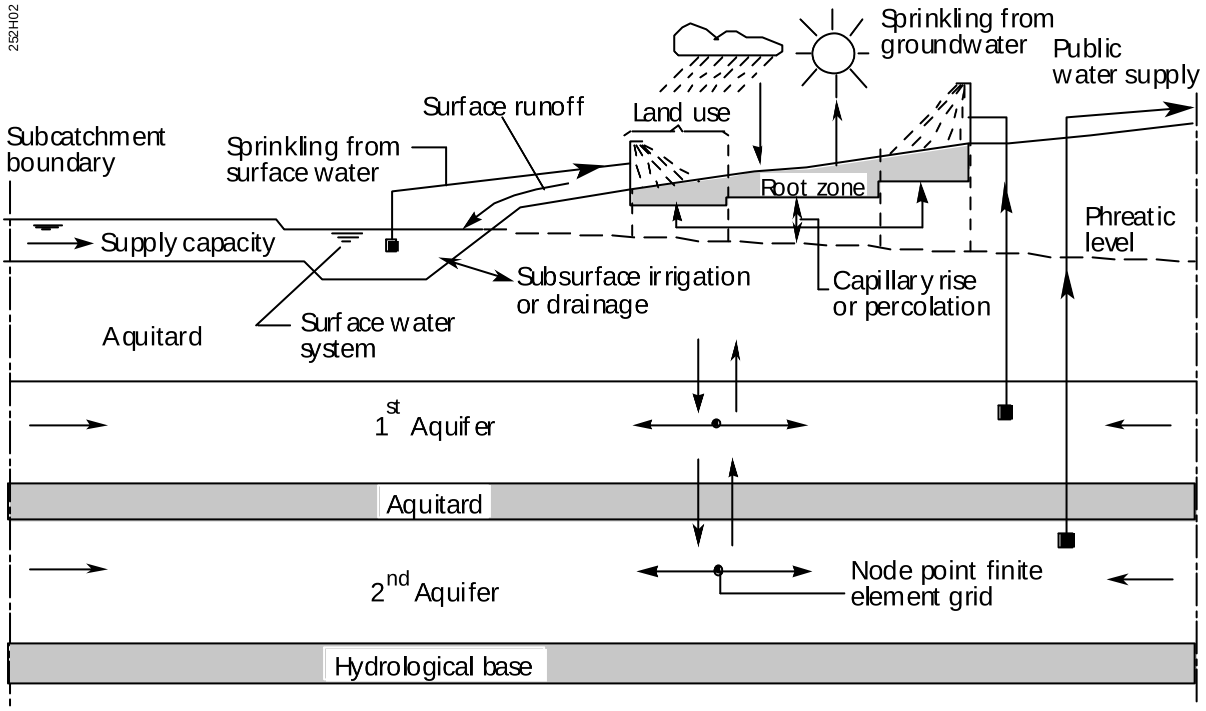


Figure 3.2 Schematization in SIMGRO of the hydrological system within a nodal subdomain by means of an integration of saturated zone, unsaturated zone and surface water (Querner and Van Bakel 1989).



3.2 Implementation of SIMGRO for the study region

3.2.1 Spatial discetisation and time steps

SIMGRO has a finite-element discretisation of the regional domain for describing the spatial aspects. Constructing triangles between nodes forms the finite elements. For each node a so-called nodal subdomain can be geometrically inferred. For the study region there are 12 000 nodes that form about 25 000 triangles. This spatial discretisation covers a larger area than the study region, in order to avoid gross inaccuracies near the borders. Thus the ‘model region’ covers some 67 000 ha, whereas the ‘study region’ roughly covers 45 000 ha. Along the main streams the distance between the nodes has been made smaller (100 m) in order to model the processes along the stream valleys more accurately. This is especially important for modelling inundation processes and for computing the seepage that is ecologically relevant. If the distance between the nodes is chosen too large, then the seepage in the stream valleys is averaged out. The consequence of this averaging out is that the reaching of critical thresholds is not predicted correctly.

The groundwater and surface water submodels of SIMGRO each run with a time step that is tuned to the type of dynamic behavior. The groundwater submodel has a time-step of 0.25 day and the surface water submodel has a time step of 0.025 day. Model output of the surface discharges are however integrated and averaged over the time period of one whole day, because the dimensioning of water channels in the Netherlands is based on the frequency distribution of such daily averages.

3.2.2 Groundwater

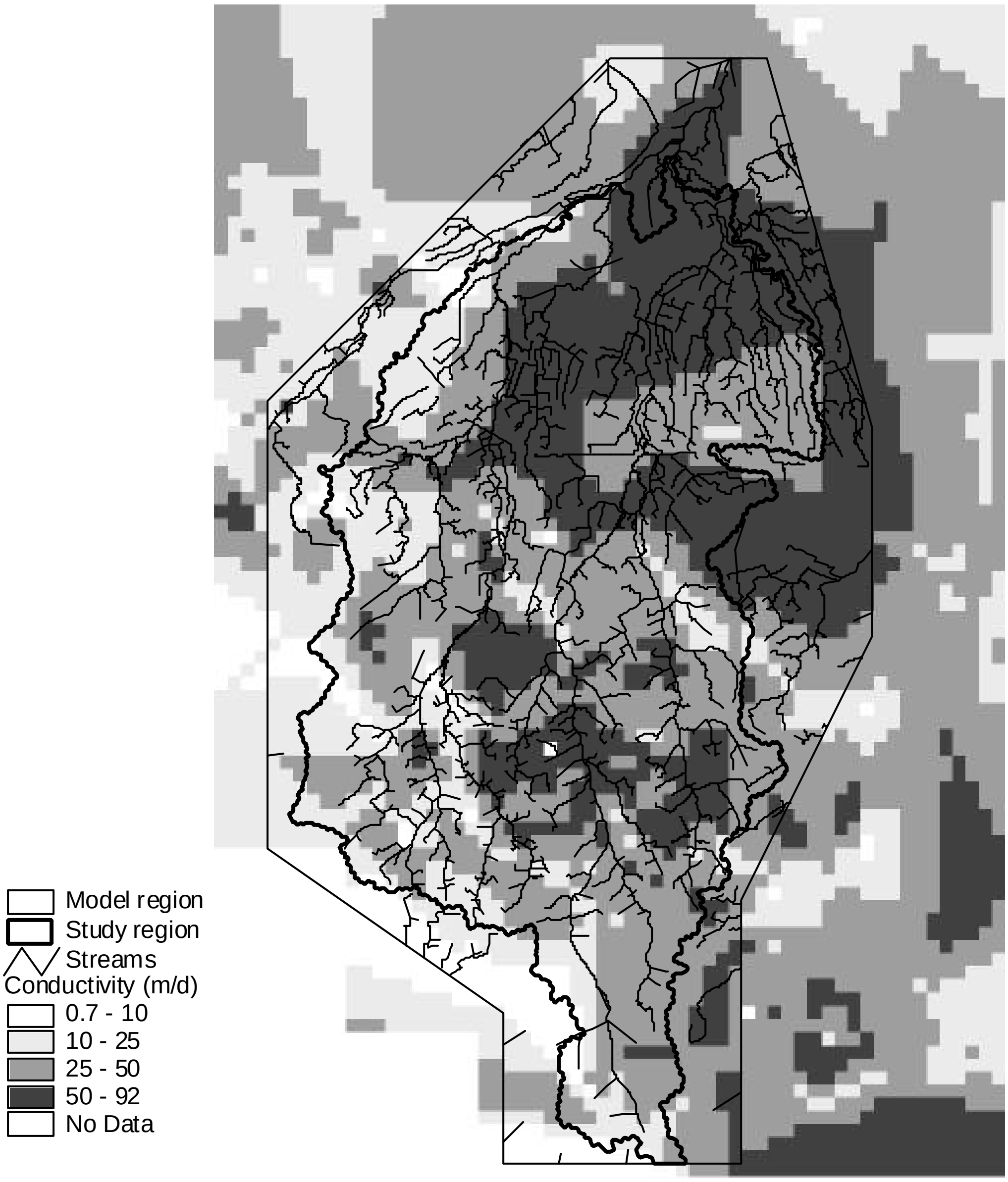
Schematisation of the subsoil

The groundwater flow in the subsoil is modeled using a schematization into layers involving horizontal flow, the aquifers, interspersed by layers involving only vertical flow, the aquitards. The used schematisation has been provided by NITG-TNO through their REGIS system (NITG-TNO 1994a). The schematisation involves in total 15 layers, which are described in Table 3.1. As can be seen from the table several of the formations have been split into an aquifer and an aquitard. For each of the layers the REGIS-system has provided a map of the conductivity and a map of the layer thickness. An example of a map of the conductivity is given in Figure 3.3, which shows the conductivity of the Sterksel/Nuenen coarse layer, the layer that plays a crucial role in determining conditions near the soil surface.

Table 3.1 Schematisation of the subsoil of the study region Beerze & Reusel, provided by NITG-TNO through the REGIS database (NITG-TNO 1994a).

Layer	Formation	Type
1	Nuenen fine sand	aquifer
2	Nuenen loam	aquitard
3	Sterksel/Nuenen coarse	aquifer
4	Kedichem/Tegelen clay	aquitard
5	Kedichem/Tegelen fine sand	aquifer
6	Tegelen clay	aquitard
7	Tegelen gravel	aquifer
8	Maassluis/Belfeld clay	aquitard
9	Belfeld gravel	aquifer
10	Kallo/Reuver clay	aquitard
11	Schinveld sand	aquifer
12	Oosterhout,/Brunssum clay	aquitard
13	Zanden van Pey	aquifer
14	Brunssum clay	aquitard
15	Waubach sand	aquifer

Figure 3.3 Example of a map of the subsoil conductivity, provided by NITG-TNO through the REGIS-database for the ‘Sterksel/Nuenen coarse’ layer (layer 3, Tabel 3.1)



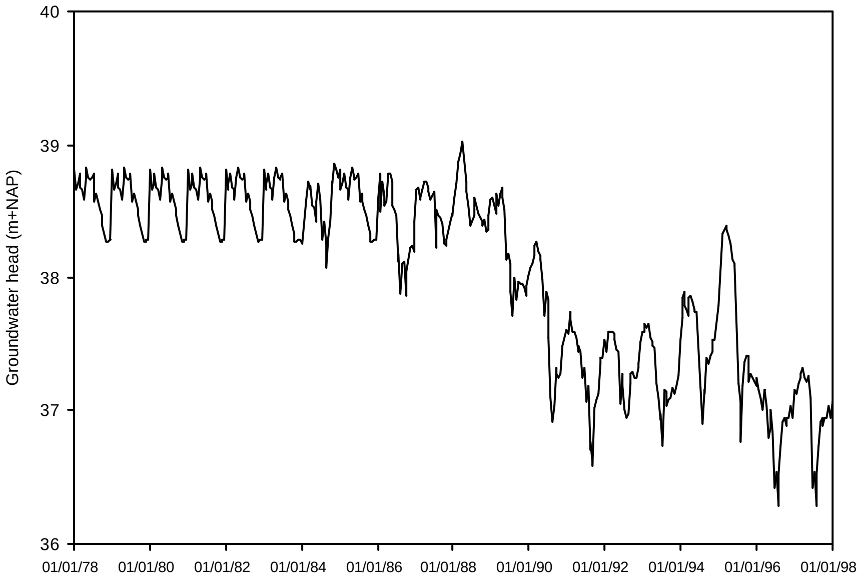
Boundary conditions and groundwater extractions

For being able to simulate the regional groundwater flow it is necessary to have information about the conditions along the boundary of the model region. For very large drainage basins the flux along the border can be set to zero without making significant errors. However, for an intermediate-size basin it is of great importance to get as accurate as possible information. Preferably this information should concern a boundary condition of the 'third kind', which gives a relationship between the head at the boundary and the flux across it. Like in most cases such information is not available. So instead information about the groundwater head has been used, from the following two sources:

- the NAGROM model for the Netherlands (De Lange 1991)
- the OLGA database (NITG-TNO 1994b)

The NAGROM-model has the advantage that it covers all depths along the boundary, even though there are less layers (6) than the 15 layers of the REGIS schematisation. The disadvantage of NAGROM is, however, that it is steady state. It is known that during the last

Figure 3.4 Time series of groundwater heads at OLGA-measurement station 57AP0025, depth of filter at –44 m+NAP. The time series has been used for superimposing the yearly and long-term trend of deep groundwater heads on the steady-state boundary conditions provided by NAGROM.



decade a sharp decrease of watertables has steadily been taking place. Also within the years themselves there are variations according to the seasons. In order to take both these long-term and annual changes into account we have used a measuring well thought to behave in a way that is representative for the regional system and have superimposed the fluctuations on the information provided by the NAGROM-model. The used series is shown in Figure 3.4.

In the region there are substantial extractions for drinking water supply and industry: these extractions total 25.5 million m^3/yr, which for a total model region of 67 000 ha is about 37 mm/yr. The main extraction is 8.5 million m^3/yr and is located just outside the study region on the eastern side.

3.2.3 Soil water and plant-atmosphere interactions

Schematisation, land use and evapotranspiration

The dynamics of soil water are modeled as vertically oriented, one-dimensional models. Per nodal subdomain the dominant land use is determined for being modeled. The main forms of land use are tabulated in Table 3.2 .

Table 3.2 Types of land use in the study region (only types with an area >1% have been tabulated).

Type of land use	Area (% of region)
grassland (agriculture)	46.6
maize	13.6
potatoes	2.6
beets	1.1
horticulture	1.9
deciduous forest	3.8
coniferous forest	17.6
heather	1.0
natural grassland	2.1
built-up area	4.9
grass in built-up area	2.1
rest	2.7
total	**100.0**

Evapotranspiration is computed in two steps:

- computation of the potential evapotranspiration by multiplying the Makkink reference crop evapotranspiration by a crop-specific factor
- computation of the actual evapotranspiration by (if necessary) reducing the evapotranspiration in situations with a moisture deficit

This method is described in Feddes (1987).

Water balance of the unsaturated zone and the shallow groundwater

The 1-D column model consists of two reservoirs, one for the root zone and one for the subsoil. If the equilibrium moisture storage for the root zone is exceeded, excess water will percolate to the saturated zone. If the moisture storage is less than the equilibrium moisture storage, upward flow from the saturated zone is simulated through capillary rise. The height of the phreatic surface is calculated from the water balance of the subsoil, using a storage coefficient that is dependent on the depth of the watertable. This function for the storage coefficient is derived by making a sequence of calculations with the steady-state model CAPSEV of the unsaturated zone (Wesseling 1991).

Storage of water on the soil surface

For modelling situations with inundation it is necessary to simulate the storage of water on the soil surface. This is done in SIMGRO using an inundation curve giving the relationship between the watertable and the fractional area of a nodal subdomain that is inundated. This inundation curve is added to the storage coefficient for the unsaturated zone, yielding an integrated water storage curve for the phreatic watertable. In this way inundation is modeled as ‘visible groundwater’.

3.2.4 Surface water

Schematisation

In the Netherlands, the surface water system often consists of a dense, complex network of water conduits with lots of hydraulic features. In a simulation model at regional scale like SIMGRO it is not feasible to explicitly account for all these conduits and their interconnections individually (Querner and Van Bakel 1989). For this reason only the larger conduits are explicitly included in the schematisation. The smaller ones area assumed to be equally distributed over the nodal subdomain that they are within. So only the first two classes of conduits are explicitly modeled of the 5 classes that are distinguished in SIMGRO. These 5 classes are:

- 1st order conduits: rivers, canals
- 2nd order conduits: large streams, large brooks
- 3rd order conduits: small streams, small brooks, ditches
- 4th order conduits: drain pipes, collector drains
- 5th order conduits: trenches, furrows, soil surface

In this classification the 5th order is of special interest. This order of conduits is used in the model to also model the soil surface: when the groundwater rises to the soil surface the soil surface itself starts to act as a drain. This process is of special relevance to this study, because the drainage over the soil surface is one of the main causes of high discharges under extremely wet conditions.

The water levels in the conduits that are explicitly modeled (1st and 2nd order) are assumedly propagated to the smaller conduits within a subcatchment. The SIMGRO model has various options for representing this. The basic ones are:

- propagation parallel to the soil surface;
- propagation on a horizontal plane

The first option applies to conditions that normally prevail in agricultural areas without weirs. In those areas the surface water network will generally have been dimensioned in such a manner that the discharge capacity is tuned to the circumstances. The latter option is usually relevant in case there is a weir, or under conditions involving infiltration and/or inundation.

In the study region the structure of the surface water network was derived from data supplied by the waterboard. Intensive data-analysis and correction procedures were needed to bring the data into order. In the data-processing procedure the streams and canals were also divided into 2350 subtrajectories of at most 500 m, which was needed for the modelling.

Interaction between groundwater and surface water

The interactions between groundwater and surface water are simulated for each nodal subdomain. A drainage/infiltration flux is computed per order of surface water conduits by dividing the difference in head through the drainage resistance. Fluxes are only computed for conduits that are ‘active’. A conduit is active if one of the following conditions is met (or both):

- the watertable is above the bottom of the conduit
- the surface water level is above the bottom of the conduit

The drainage resistance is considered to have three components:

- the resistance involved in transporting drainage water horizontally towards the conduit, which is computed with a conventional drainage formula (see Veldhuizen *et al*. 1998)
- the resistance involved in the radial flow in the direct vicinity of the conduit
- the resistance involved in the entrance to the conduit, caused by loamy material in the conduit walls

In practice it is hard to distinguish between the latter two types of resistance. They therefore are usually combined into a composite resistance γ_r. It has been found that a value of 0.8 d/m is a good first guess for it. The actual drainage resistance is then found by multiplying this resistance by the mean distance between the conduits:

$$\gamma = \gamma_r \cdot L + \gamma_h \tag{3.1}$$

in which:

- γ : drainage resistance (d)
- γ_r: radial/entrance resistance (d/m)
- L : mean distance between conduits (m)
- γ_h : ‘horizontal’ drainage resistance (d/m)

The mean distance between conduits is found by dividing the area of a nodal subdomain by the sum of the lengths of the conduits, assuming that the conduits are equally distributed over the nodal subdomain:

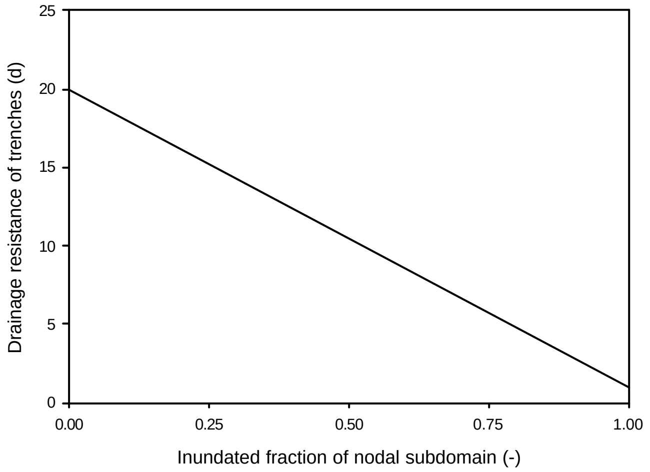
$$L = A / \Sigma l \tag{3.2}$$

in which:

- Σl : sum of lengths of a conduit of a certain order (m)
- A : area of a nodal subdomain (m^2)

Figure 3.5 Drainage resistance of trenches/furrows as a function of the fractional inundation.

A fractional inundation of 0.50 corresponds with a watertable equal to the average soil surface elevation in a nodal subdomain.



In the computation of the drainage resistance for the larger conduits the mean distance L soon becomes larger than the cross-section of a nodal subdomain. In that case not L is used, but the cross-sectional distance of the nodal subdomain. This provision is necessary to avoid double counting of horizontal resistances in the model: the groundwater flow between the nodes themselves is computed with the finite element scheme.

The 5th order drainage plays a special role in the model, because it is also used for modelling the surface runoff that occurs when the groundwater reaches the soil surface. In the case of total inundation the flow resistance becomes small. The resistance has therefore been made dependent on the degree of inundation. On the basis of past experience we have set the value for complete inundation at 1 d. For fractions of inundation between 0.0 and 1.0 the resistance is varied linearly, starting from 20 d for situations with no inundation (Figure 3.5).

Dynamics of surface water

The surface water system is modeled as a concatenation of reservoirs, each one controlled at the outlet by a weir or an imaginary one, using a tabulated Q-h relation. This Q-h relation implicitly accounts for all hydraulic features within the reservoir in a 'black box' manner. That includes also the conditions at bifurcations, of which there are about 10 in the study region. Bifurcations are present at places where the waterboard has made a parallel conduit – which then becomes the new main stream – to reduce the inundations around the old main stream.

3.3 Calibration

3.3.1 Introduction

Even for a ‘physically based’ model like SIMGRO some form of calibration is inevitable. In the current practice of groundwater modelling the use of automated parameter fitting procedures is becoming more and more prevalent. An example of a much used software package is PEST (Dougherty 2000). Such software has, however, not been used in the current study. There are various reasons for this. Firstly, the running of the SIMGRO model used in this study (12 000 nodes, 15 layers) takes roughly an hour of CPU-time per year of simulation. For purposes of automated fitting that is very unwieldy. Secondly, we did not only use head data, but also looked at the discharges. That makes it hard to find a suitable goal function. Thirdly, even with the use of automated procedures one can not escape from specifying the bounds for realistic values of parameters. That usually is done manually anyhow, largely determining the outcome of the calibration.

It is also the opinion of the authors that the use of automated calibration methods does not at all guarantee that the produced results are better than when the calibration is done ‘by hand’. At most automated calibration methods can reduce the amount of time involved in the calibration process. The geostatistical interpretation of the parameter covariances that are computed is extremely hazardous if not all of the relevant system parameters are taken into account.

3.3.2 Available data and calibration criteria

The following sources of data have been used:

- a map of the Mean Highest Watertable (Kleijer *et al*. 1990)
- a map of the Mean Lowest Watertable (Teunissen van Manen 1985)
- data of watertable gauging wells registered in the OLGA-database (NITG-TNO 1994b)
- discharge measurements of the Reusel and the Beerze
- amounts of sprinkling in the Hilver land reconstruction area (Van der Bolt *et al*. 1999)

In the Netherlands maps of Mean Highest Watertable (MHW) and Mean Lowest Watertable (MLW) are widely used for characterizing the groundwater regime. The definition of the Mean Highest Water table is as follows:

- from a series of gauged watertables on the 14th and 28th day of each month the three highest levels are selected for each of the gauging years
- per gauging year the average of the three selected levels is taken, yielding the so-called HG3-level for each of the available years
- the HG3-levels are averaged over the years, yielding the MHW-value

The revised map of the MHW for 1990 is given in Figure 3.6a. Even though this map is fairly recent, it should be realized that in the past ten years changes have taken place causing further desiccation in the region (Figure 3.4). The Mean Lowest Watertable is derived in a similar fashion. The map given in Figure 3.6b has been made by the former soil survey institute STIBOKA in the early 1980's (Teunissen van Manen 1985). More than 20 years have gone by since it was made, so this map is out of date. But in practice the map of MLW is less susceptible to change than the one of MHW, so the available map of MLW still contains valuable information.

Only limited information is available on the amount of sprinkling in the region. According to a survey done for the rural reconstruction project Hilver (Van der Bolt *et al.* 1999) the average amount of sprinkling is roughly 16 mm per year, averaged out over the gross area (including non-agricultural areas).

Comparisons between calibration runs have been made through visual means, using maps (watertables) and exceedance frequency curves (discharges), and through using numerically defined criteria. For comparing the simulated and measured maps of Mean Highest and Mean Lowest Watertable the calibration criteria are in terms of class differences. Use had to be made of classes because the measured maps are only available in that form. For instance for the Mean Highest Watertable the following function has been used:

$$E_{MHW} = (1 - \Sigma \mid MHW_m - MHW_s \mid / N) \times 100\% \qquad (3.3)$$

in which:

- E_{MHW} : model efficiency for simulating the Mean Highest Water table (%)
- MHW_m : class of measured Mean Highest Watertable for a pixel (-)
- MHW_s : class of simulated Mean Highest Watertable for a pixel (-)
- N : number of pixels

So if the average deviation is one class, the computed efficiency is zero.

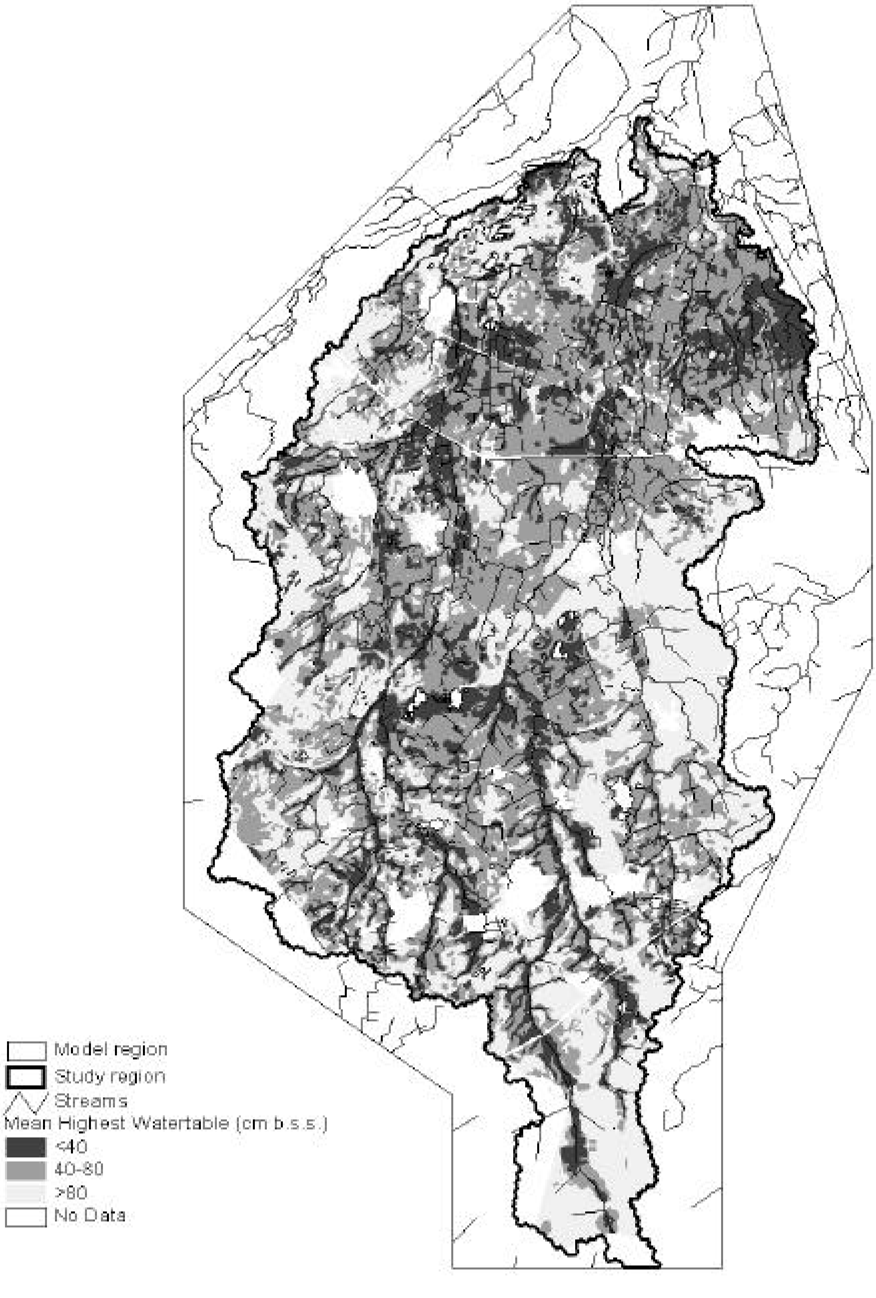
For the discharges the following statistics have been used:

- average flow difference, Δq (% of mean discharge)
- goodness of fit, E_q (%)

The used 'goodness of fit' criterium for the discharges is the well-known function proposed by Nash & Sutcliffe (1970):

$$E_q = (1 - \Sigma\,(q_m - q_s)^2 / \Sigma\,(q_m - q_{m,a})^2\ ) \cdot 100\% \tag{3.4}$$

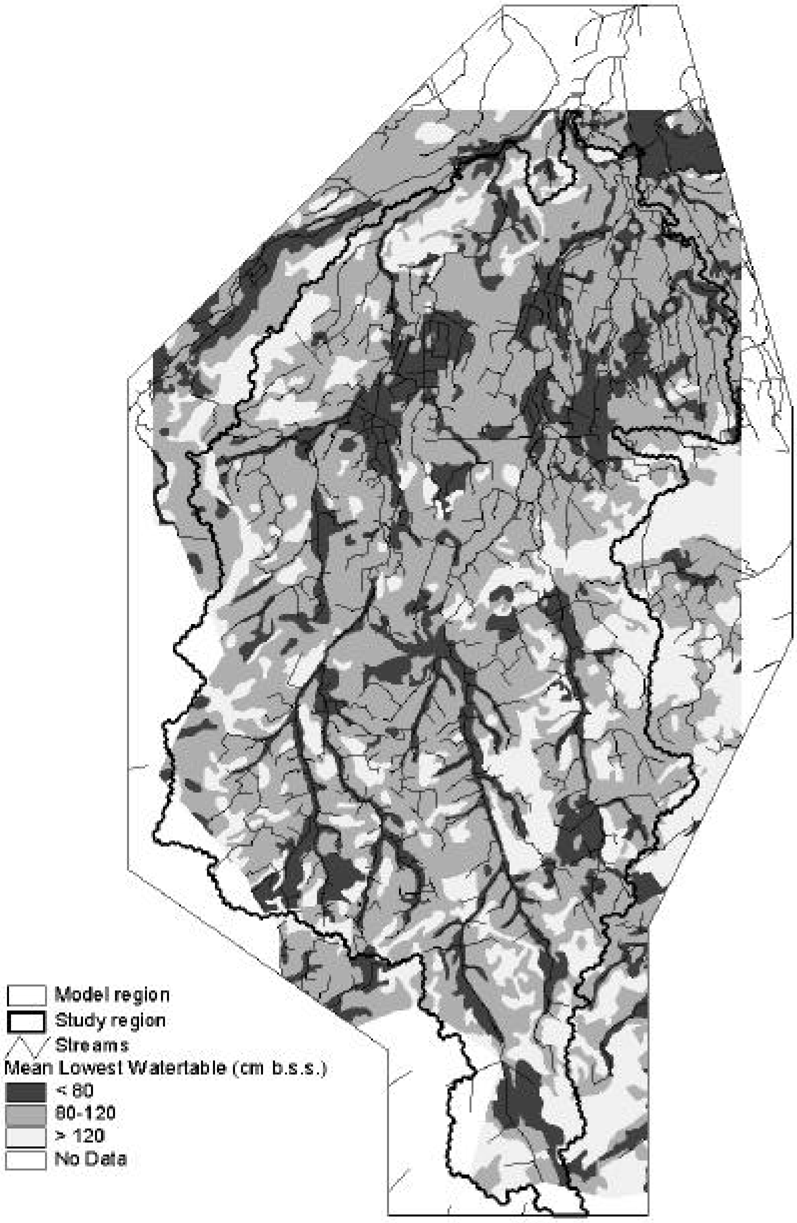
Figure 3.6a The Mean Highest Watertable for the study region (Kleijer *et al*. 1990)



in which:

- E_q : model efficiency for simulating discharges (%)
- q_m : measured discharge (l/s)
- $q_{m,a}$: average measured discharge (l/s)
- q_s : simulated discharge (l/s)

Figure 3.6b Map of Mean Lowest Watertable (Teunissen van Manen 1985).



3.3.3 Results for the uncalibrated model

The results for the uncalibrated model are shown in the form of the Mean Highest Watertable MHW in Figure 3.7 and the exceedance frequencies of the simulated and measured discharges of the Beerze and the Reusel in Figure 3.8. The run with the model was done for 1980-90, i.e. the same period as of the available MHW-map. The following calibration criteria values were found:

- E_{MHW} = 52%; E_{MLW} = 80%
- $E_{q,R}$ = 58% (Reusel); $E_{q,B}$ = 75% (Beerze)

Figure 3.7 Map of the Mean Highest Watertable, simulated by the uncalibrated model. Downscaling is done using the procedure described in Section 5.2

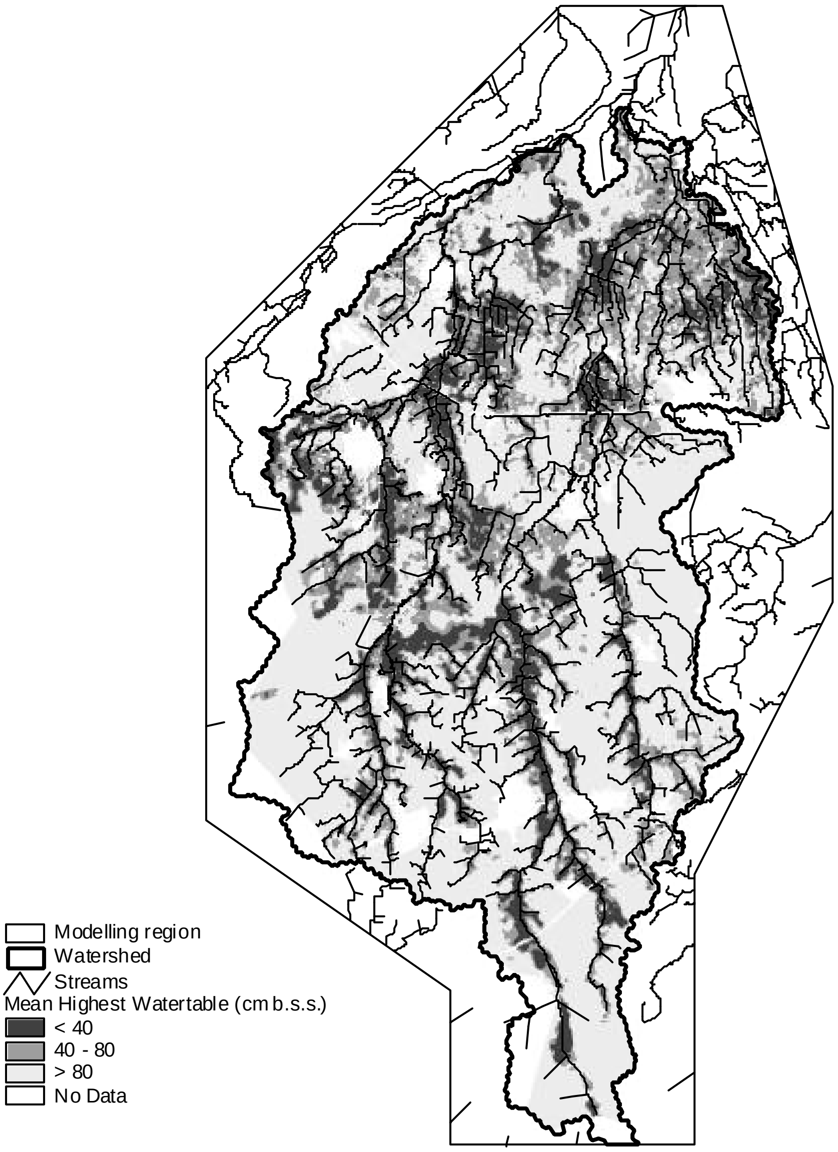
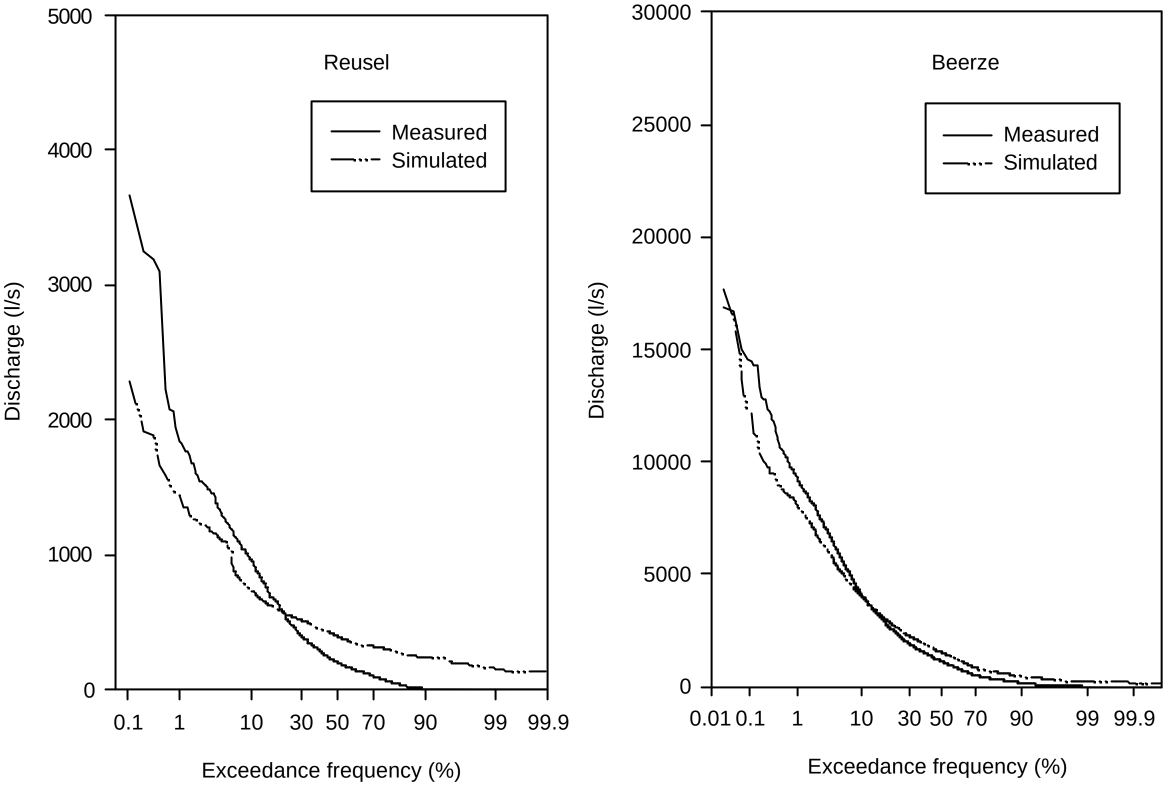


Figure 3.8 Exceedance frequency curves for discharges of the Beerze and Reusel, simulated by the uncalibrated model.



Comparison of the simulated and measured maps of the Mean Highest Watertable shows that the errors are mainly made along the flanks of the valleys: the simulated maps show an abrupt change from very wet conditions to very dry ones, whereas the measured map shows that also higher up on the valley slopes a large percentage of the area remains in the second class with Mean Highest Watertables between 40 and 80 cm b.s.s. (cm below soil surface). A visual inspection of the discharge exceedance frequency curves shows a big difference in behavior for the Reusel. The simulated peak discharges are far lower than the measured ones, and the low flows continue much longer in the model than in reality.

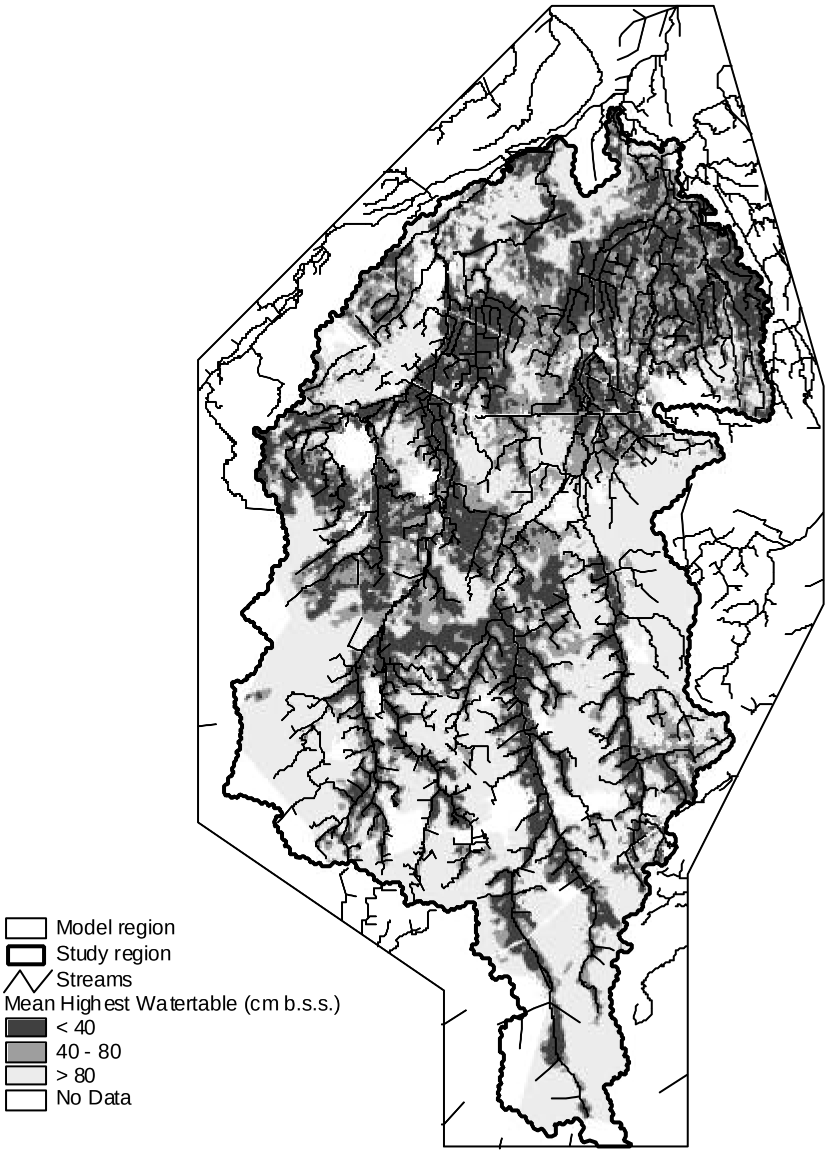
3.3.4 Adjustment of parameters

Preliminary analysis of main parameters to be calibrated

Initially the sprinkling capacity was set to 1.00 mm/d for all agricultural crops. The computed long-term average of the sprinkling amount was found to be 24 mm/yr, if the sprinkling is averaged out over the whole region. That is 1.5 times the 16 mm/yr found in the Hilver rural reconstruction area (Van der Bolt *et al.* 1999). For this reason the sprinkling capacity of crops was lowered to 0.67 mm/d.

The next calibration question concerns the main cause of the differences between measured and simulated data: are they caused by the geohydrological parameters of the subsoil, the drainage resistances, or other parameters? To investigate the influence of the drainage resistances a calibration run was made with all the entry resistances of streams, ditches and drains set to 4.0 d, which is extremely high. The result for the simulated map of the Mean

Figure 3.9 Map of the Mean Highest Watertable, simulated after setting the entry resistances of the streams, ditches and drains at 4.0 d (extremely high).



Highest Watertable is shown in Figure 3.9. As can be seen from the map the simulated conditions in the stream valleys become even more wet, whereas the conditions on the higher grounds along the stream valleys are still too dry. The reason for this local effect on the conditions along the streams is that the drainage resistances are only active in the model nodes where the groundwater is above the bottoms of the waterways, which is at the bottom of the valleys. Increasing the resistances causes the groundwater to reach the soil surface along the streams, because the soil surface is the only remaining route for the water to leave the groundwater system and enter the stream, since the other resistances have been set very high. The effect of setting the drainage resistances very high is also reflected in the computed criteria for the Mean Highest and Mean Lowest Watertable:

- E_{MHW} = 58% (was 52%)
- E_{MLW} = 74% (was 80%)

On the basis of the criterium E_{MHW}, the similarity between simulated and measured maps has become better, but judged 'visually' the pattern has decidedly become a worse fit. Also the similarity with respect to the Mean Lowest Watertable has become worse. In conclusion, sharply increasing the drainage resistances is not the right course of action to improve the model.

From the above computational experiment it has become clear that the drainage resistances are not the main cause for the differences between measured and simulated variables. Instead, the images of the simulated watertables indicate that the initial estimates of the geohydrological conductivities are far too high. Owing to these high values the groundwater can flow without much of a gradient towards the valleys, to where the streams are. This leaves the valley flanks high and dry. Inspection of the geohydrological data revealed that for instance the conductivities of the first layer – modeled as an aquifer – range between 2 and 100 m/d. Considering that this concerns fine-sandy sediments, such a range seems to be unrealistic. Values of up to a maximum of 5-20 m/d are what one would expect. Also the initial estimates of the third layer – the Formation of Sterksel – seem to be unrealistically high: the conductivity ranges between 0.7 and 92 m/d, with 75% of the values higher than 25 m/d. This formation is reputed to have conductivities between 20 and 30 m/d (Negenman *et al.* 1998). So both information from other sources about the conductivities themselves and also the initial results of the uncalibrated model pointed towards the necessity of lowering the conductivity values in the course of the calibration.

After having performed the above preliminary analysis, the following stepwise calibration procedure was decided upon:

- adjustment of geohydrological parameters of shallow layers (1 through 4)
- adjustment of drainage resistances of main waterways and streams
- adjustment of drainage resistances of field ditches and drains
- adjustment of trench resistances

Adjustment of geohydrological parameters of the shallow layers

The following modifications were made (the numbering corresponds to the numbers of calibration runs in Table 3.3):

- the conductivity of the first layer was reduced through the operation $k' = 2*\sqrt{k}$; by taking the square root most of the reduction is on the high values, whereas the lower values are modified less; this does not change the regional pattern of watertables very much, however (calibration run 3 of Table 3.3)
- in the south-western quarter of the study region (the higher ground in the Reusel basin) a resistance was introduced in the second layer of 3000 d, and the kD-value of the top layer was set to 4 m^2/d (thickness of 4 m and a conductivity of 1 m/d) (run 4)
- in the southern half of the region (to the south of the so-called Feldbiss fault) a resistance of 2000 d was introduced in the fourth layer (run 5)
- the conductivity of the Sterksel Formation (layer 3) was reduced through the operation $k' = 3*\sqrt{k}$; this brings the range of conductivities within the 0-30 m/d interval reported by Negenman *et al.* (1998) (run 6)

The results for the calibration criteria are summarized in Table 3.3, runs 3 – 6. As can be seen from the table, the efficiency criterium for the Mean Highest Watertable is substantially improved, without hardly decreasing the efficiency criterium for the Mean Lowest Watertable.

Adjustment of drainage resistances

On the basis of field knowledge and the density of the waterways it was concluded that in the northern part of the study region there must be relatively more loamy material in the shallow subsoil than in the southern half. It was therefore decided to differentiate the entry resistance

Table 3.3 Values of calibration criteria for the calibration runs. E_{MHW} and E_{MLW} : efficiency parameters for the fit of the Mean Highest and Mean Lowest Watertable; $E_{q,R}$ and $E_{q,B}$: efficiency parameters for the simulated discharges of Reusel and Beerze. The mean flows are evaluated in terms of the percentage difference between simulated and measured (positive values mean that the simulation is higher).

Run	Short description of calibration run	E_{MHW} (%)	E_{MLW} (`%)	$E_{q,R}$ (%)	$E_{q,B}$ (%)	Δq_R (%)	Δq_B (%)
1	Initial estimate	51.7	79.6	58.1	75.1	29.1	12.3
2	High drainage resistances waterways	58.2	73.5	62.2	78.0	21.9	6.8
3	Reduction of 1st layer conduct. k’=2*√k	52.7	79.2	59.3	75.5	26.9	11.1
4	Resistance 2nd layer 3000d, southwest	54.6	79.0	65.9	75.6	21.5	10.5
5	Resistance 2000d 4th layer, south	54.6	79.1	65.8	75.4	22.0	10.5
6	Reduction of 3rd layer conduct.k’=3*√k	55.9	79.1	66.4	74.7	22.9	7.7
7	Increase of entry resistance of streams in northern half from 0.8 d to 1.2 d.	56.5	79.0	66.4	74.7	22.8	7.5
8	All entry resistance streams +25%	56.8	78.7	66.6	74.8	22.5	7.2
9	All entry resistances streams +60%	57.1	78.3	67.0	74.9	21.9	6.6
10	Agricultural drainage included	58.2	79.5	68.2	75.1	23.2	7.4
11	Resistance of trenches 10 d	58.2	79.5	69.3	75.2	23.1	7.4
12	Resistance of trenches 30 d	58.2	79.5	67.4	75.0	23.3	7.3

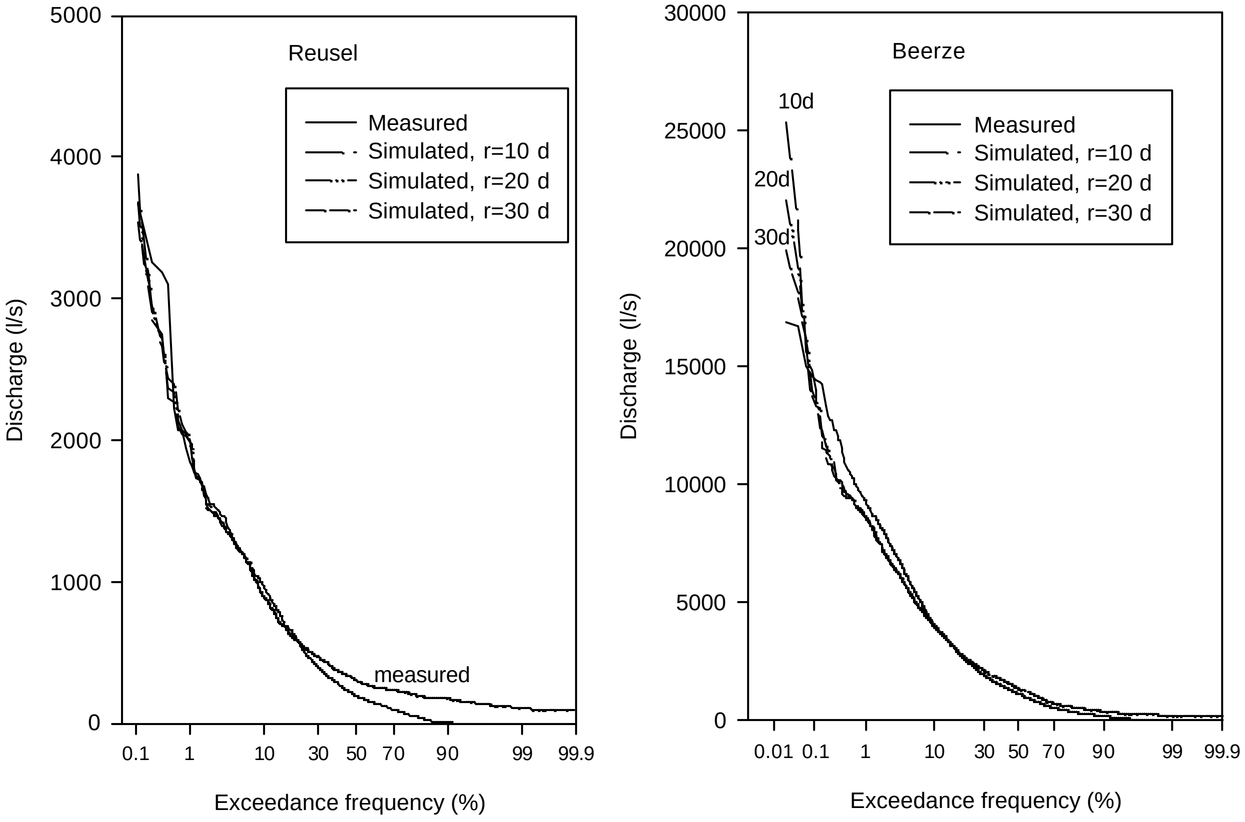
of the waterways: the values in the northern half were increased from 0.8 d to 1.2 d. This gave a small but significant improvement of the calibration criterium for the MHW (run 7 in Table 3.3). After having made this differentiation a systematic sensitivity analysis was performed for the entry resistances of the streams. The values for the whole region were simultaneously changed in the same proportionate manner: the values were increased by 25% (run 8), and then by 60% (run 9). These variations did not cause significant changes in the computed calibration criteria. On the basis of a visual impression the choice was made to set the entry resistance of streams to 1.0 d in the southern half and 1.5 d in the northern half (i.e. the values of run 8). At the ‘field’ level both the ditches and agricultural drains play a role. It is hard to discern between them when attempting to make adjustments. The choice was made to leave the drainage resistances of the ditches untouched and to do the fine-tuning by introducing agricultural drainage if necessary. This was done with the following procedure:

- the simulated and measured maps of the Mean Highest Watertable are compared at the level of nodal subdomains;
- if the simulated map has a MHW in the class <40 cm b.s.s. (cm below soil surface) and on the measured map it is drier (>40 cm b.s.s.), and the land is used for agriculture, then agricultural drainage is assumed in the nodal subdomain

The procedure has been verified by comparing the calibrated drainage with the known drainage in the Hilver region (Van der Bolt *et al.* 1999). For that part of the region the resemblance between calibrated and known drainage is well over 50% in this study. Considering that the knowledge of existing drainage is known to be partial (many of the locations are unknown) the resemblance is satisfactory as a method of calibration.

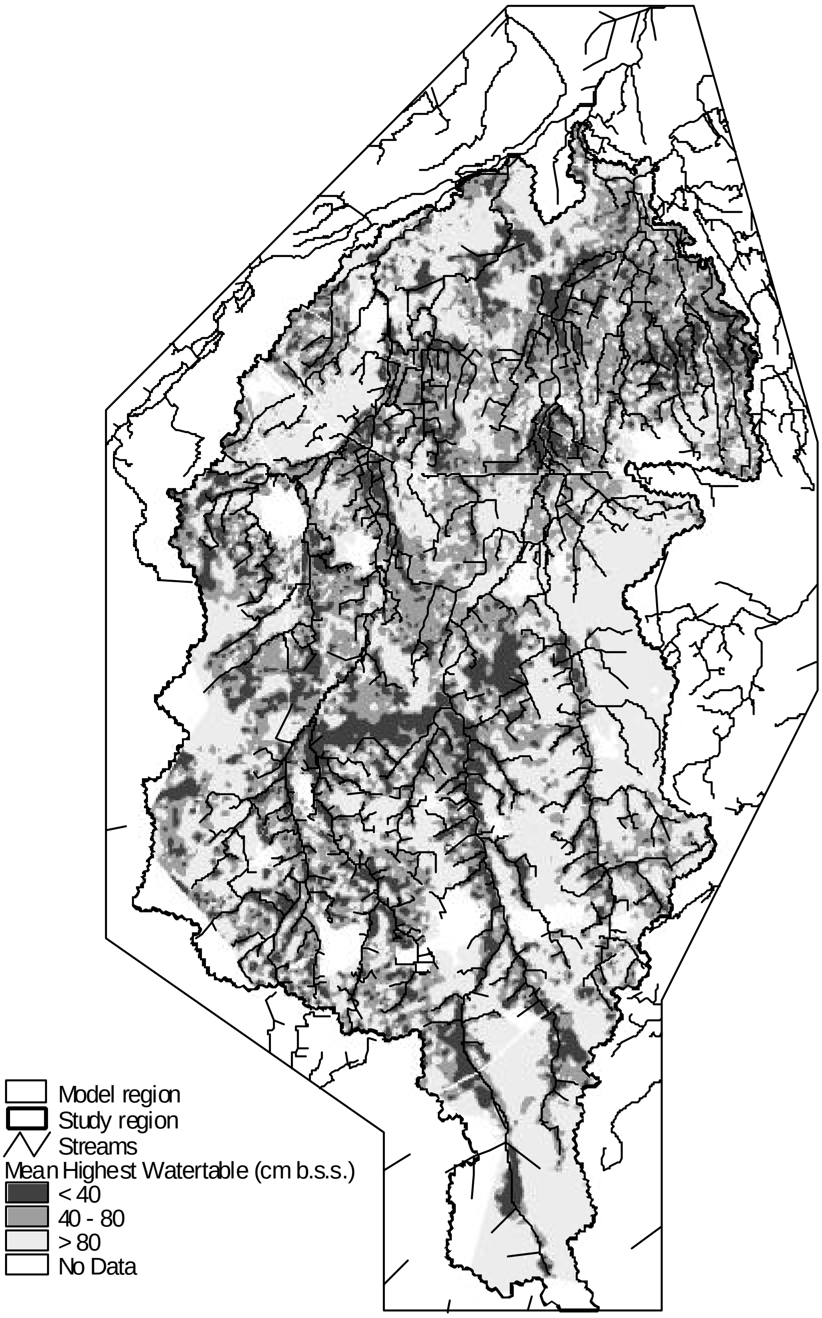
In the final phase of the calibration some experiments were done with the drainage resistance of trenches. The default value of 20 d was varied to 10 d and 30 d. The influence of these variations is shown in Figure 3.10 One should take into account that the curve for the measured discharges of the Beerze is at fault for the extreme high values at the bottom end of the exceedance frequency values. The flattening off for exceedance frequencies of less than 0.5 d per year is due to flooding of the weirs that are used for the measurements. If the measurements had been correct the curve would no doubt have followed a similar trajectory

Figure 3.10 Exceedance frequency curves for the Reusel and Beerze, for the final calibrated values of the geohydrological parameters and drainage resistances of streams and ditches, and for three values of the resistances of trenches (10 d, 20 d, and 30 d).



as the one for the Reusel: typically the curve is slightly concave. The choice for the final value (20 d) of the trench drainage resistances was fairly arbitrary. The final simulated map of the Mean Highest Watertable is presented in Figure 3.11.

Figure 3.11 Map of the Mean Highest Watertable (final calibration).



3.3.5 Verification with gauging wells of OLGA-database

The data of the gauging wells of the OLGA-database (NITG-TNO 1994b) have been reserved for the verification of the calibrated model. In Figure 3.12 the deviations between the simulated and measured heads have been plotted in terms of the mean heads per well, for the shallow (layers 1 and 3) and deeper wells separately. As can be seen from the plot on the right-hand side the simulated heads for the deep wells are nearly all higher than the measured ones. This means that the heads of the deeper layers can *not* be the cause of the model to underestimate the heads in the phreatic layer. So the underestimation of these heads (that still exists, even after reducing the conductivities during the calibration: see Figure 3.11 compared to the measured map of the Mean Highest Watertable in Figure 3.6a) must out of necessity be caused by circumstances in the upper layers, which are the layers where the conductivities have been reduced in the calibration. The results for the shallow wells in the plot on the left-hand side of Figure 3.12 show some regional tendencies:

Figure 3.12 Differences between means of simulated and measured heads for the shallow wells (in layer 1 and 3, left side of figure) and deep wells (right side).

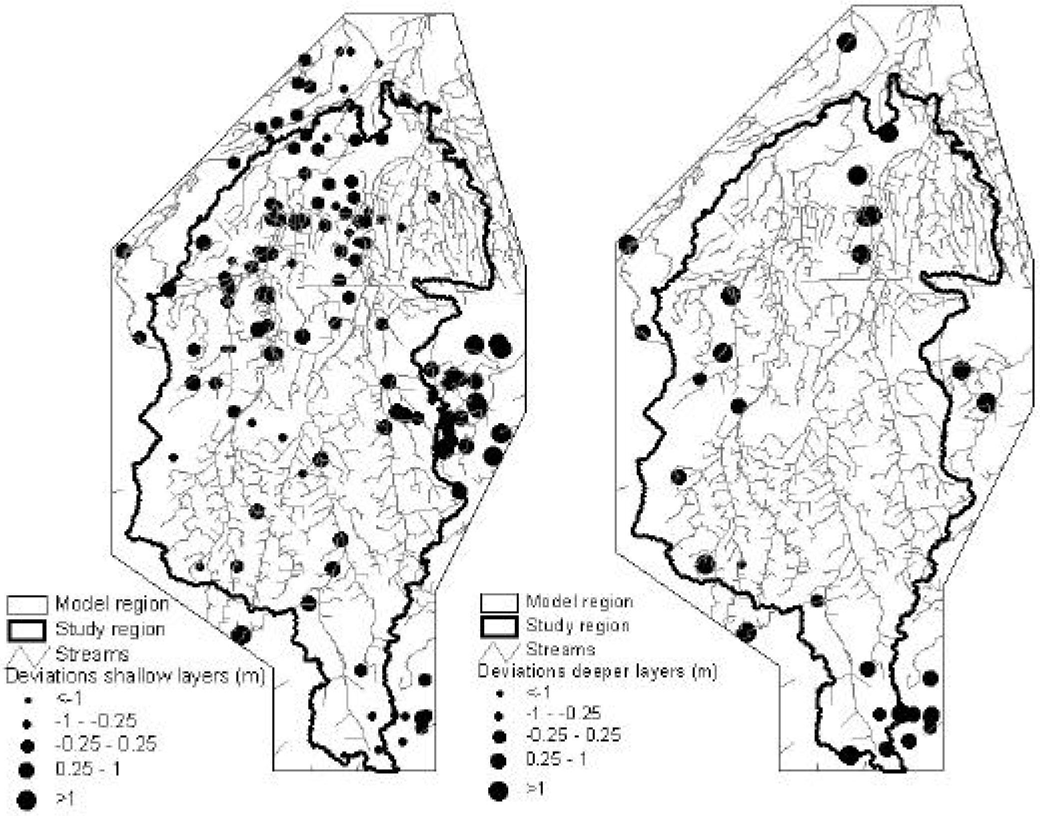
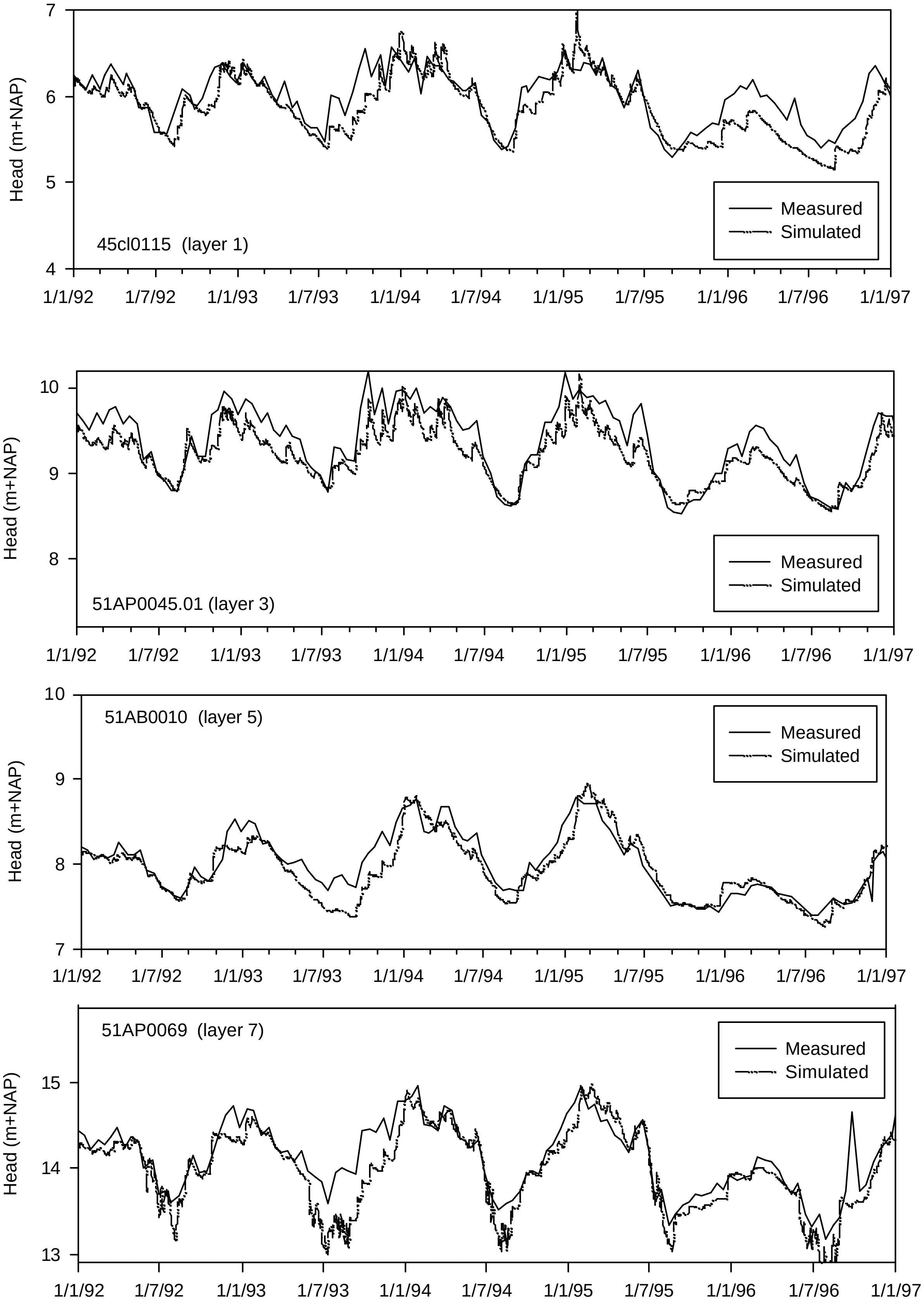


Figure 3.13 Examples of simulated vs. measured heads for geohydrological layers 1,3,5,7. The different plots refer to different locations.



- the cluster of large dots on the right-hand side of the region just outside the border of the study area are in the vicinity of a large drinking water extraction in the third layer. Apparently the model does not properly estimate the drawdown, probably because of too high conductivities in the third layer
- the large dots in the southern half of the study region are nearly all directly next to streams. So either the water levels in the streams or else the drainage resistances are overestimated. The implication is that the underestimation of the groundwater heads in the flanks of the valleys and on the higher grounds is not caused by the conditions near or in the streams. The underestimation must be caused by conductivities that are still too high
- the large dots in the western half of the plot on the left-hand side are in a part of the region that is geologically very complex, with heavy fracturing. Proper simulation of this part of the region would require much more field information

In Figure 3.13 some (good) examples of the comparison between measured and simulated time series of well locations are given.

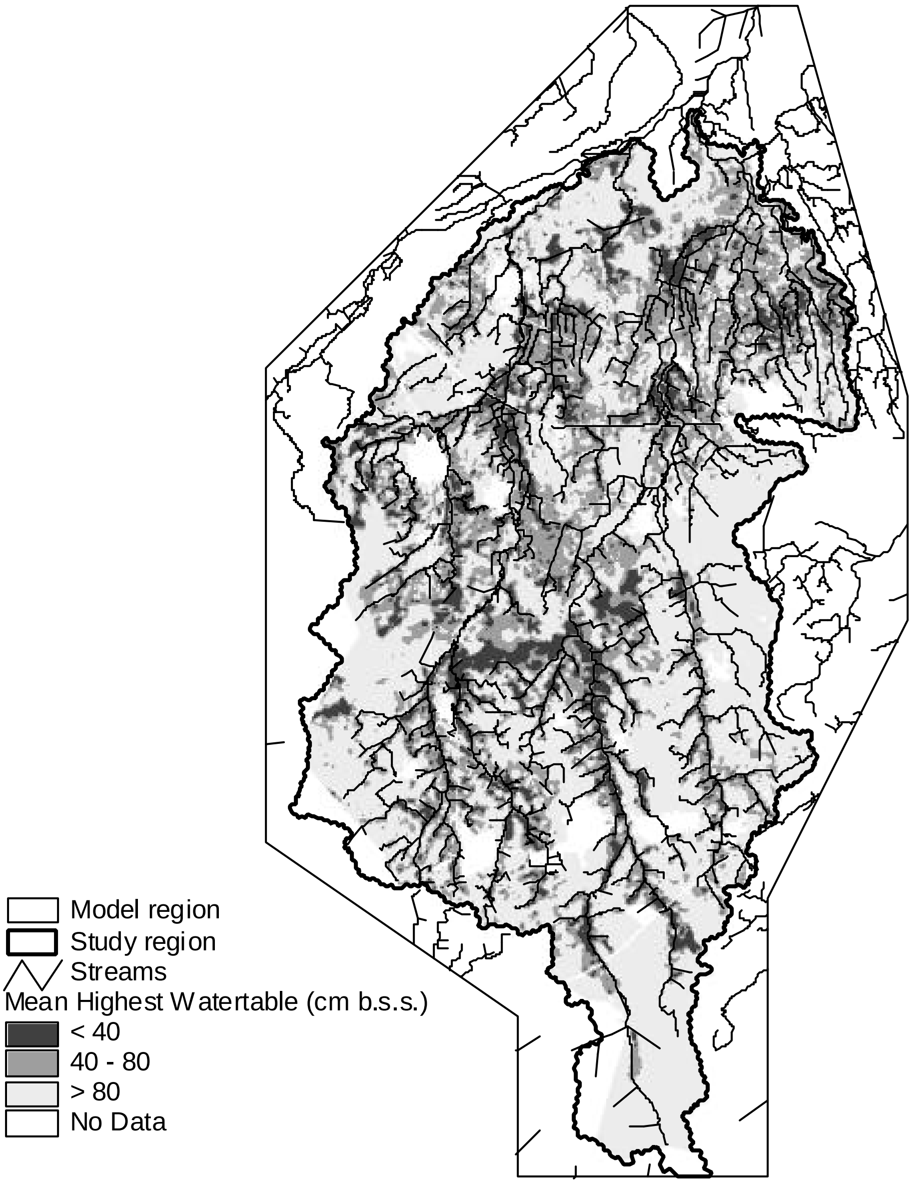
In the final evaluation of the calibration, it seems likely that further improvement of the model would have required further lowering of the conductivities of the shallow layers. This would not have only further improved the simulation of the Mean Highest Watertable, but would also have improved the simulation of the discharges with an exceedance frequency of around 1 d per year. However, further reduction of the geohydrological conductivities was considered to be out of bounds and therefore not implemented.

3.4 Results for the current situation

In the region it is known that structural changes are taking place. This can also be inferred from Figure 3.4. The dropping of the groundwater head is so systematic that it is not likely to be caused by natural climatological variations of the weather. For simulating conditions that reflect the current situation as well as possible, the final year of the heads in Figure 3.4 has been used for deriving *boundary conditions*: the daily values of the last year have been cyclically repeated for each year of the simulation period.

For simulating the current situation the meteorological data have been used for the period 1984 though 1998, i.e. a period of fifteen years. This period was selected after analyzing a

Figure 3.14 Mean Highest Watertable, simulated for the current situation.

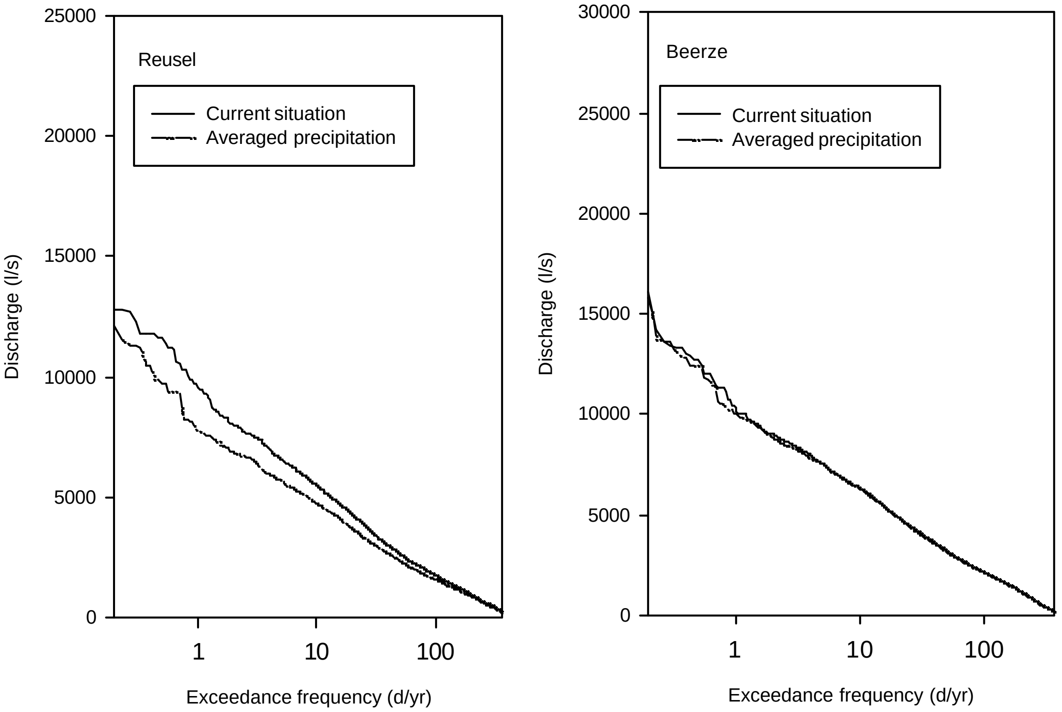


period of 30 years using data of the main meteorological station in the Netherlands. A ‘climate’ is by definition the weather that occurred during the last 30 years. The reason why the last 30 years could not be used in this study is simply that the daily precipitation data were not available for all the regional gauging stations for so long a period. In Figure 3.14 the simulated map of the Mean Highest Watertable for the current situation is presented. Comparison between the final map for the calibration period (Figure 3.11) shows that the watertables have dropped substantially within a period of 10 years.

Results for the exceedance frequency curves of simulated discharges for the Reusel and Beerze are shown in Figure 3.15. Apart from making a simulation for the current situation, a simulation has been made with the regional precipitation averaged out, with the average simply taken as the arithmetic mean of the six regional precipitation stations. As pointed out in Section 2.2.2, the average precipitation of the Beerze drainage basin is 1.5% less than the arithmetic mean of the weather stations used for the study. By contrast, the precipitation for the Reusel basin is 4.5% higher.

As becomes clear from the plots, the discharge curve for the Beerze is hardly any different. By contrast, the simulated discharges for the Reusel are nearly 20 % less (18%). This is an important fact for the interpretation of scenarios presented in chapters 8-11, because the climate scenarios have been calibrated in terms of the averaged regional precipitation. The implication is that for a certain climate scenario it can be expected that the effect on the discharge will – when compared to the current situation – be roughly 20% lower for the Reusel than for the Beerze: the averaging of the regional precipitation that is implicitly contained in the climate scenarios causes a 20% drop of the discharges for the Reusel, and not for the Beerze. For the interpretation of the scenarios it is a fortunate circumstance that at least for the Beerze there has not been introduced an extra effect due to the regional averaging.

Figure 3.15 Comparison between frequency exceedance curves of simulated discharges for Reusel and Beerze, for the current situation and for the (hypothetical) situation with the regional precipitation averaged out over 6 regional stations.



4 STREAM MORPHOLOGY

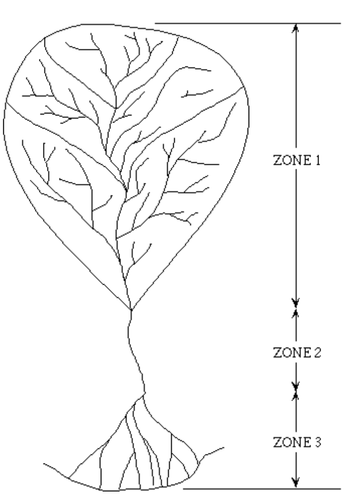
J.W.J. van der Gaast

4.1 Introduction

Streams carry water and sediment out of drainage basins and therefore reflect the nature of the hillslope and drainage basin processes and of course also the climatic forces that drive the hydrological cycle. To develop an understanding of the potential and actual changes that might occur as a result of climate change, the relevant fluvial processes should be identified. The following outline of the fluvial system is designed to provide a basic model by which the fluvial processes can be ordered. The uppermost part of the fluvial system is the drainage basin, watershed, or sediment-source area (Zone 1 in Figure 4.1). This is the area from which water and sediment are derived. It is primarily the zone of sediment production, although sediment storage does occur there too in many ways. Zone 2 is the transfer zone; for a stable channel the inflow and outflow of sediment are balanced. Zone 3 is the area of deposition, where various types of alluvial or coastal deposits can occur.

Certain aspects of fluvial systems are reasonably constant through time; for example, the length of a stream or the area of a drainage basin change only very slowly. The factors that are not constant in time or do not occur in the same way at regular intervals can consist of rare (extreme) events or of structural changes in the driving forces of the system.

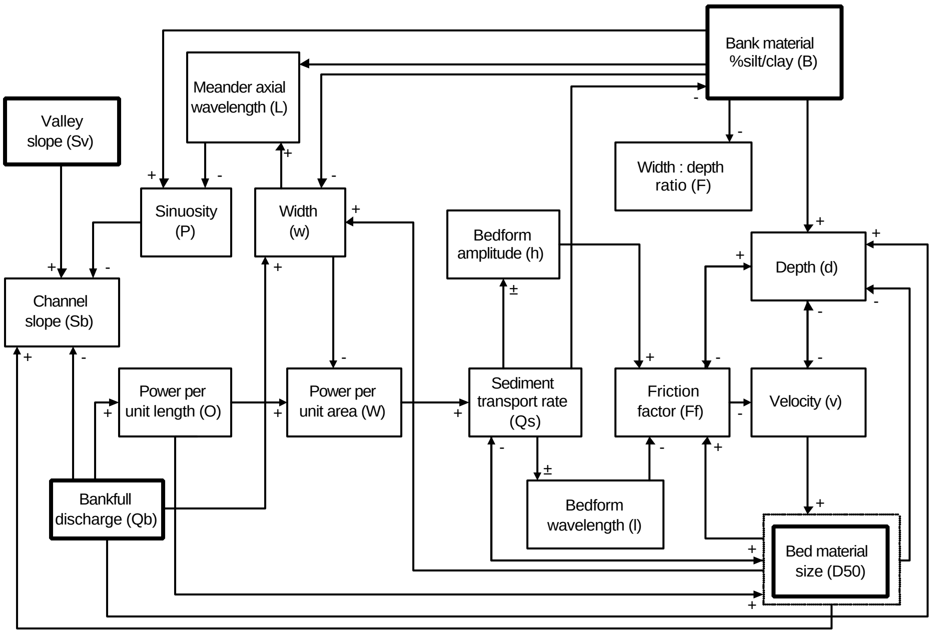
Figure 4.1 Idealized fluvial system (After Schumm 1977), with upper reaches in Zone 1, middle reaches in Zone 2, and lower reaches in Zone 3.



Climate change represents a structural shift of independent variables and affects the discharge of streams, the amount of sediment they can carry, and the amount of sediment being produced on hillslopes and transported to streams. However, within any given climatic regime, there will be very rare or infrequent events, such as a catastrophic storm, which also may play an important role in the operation of the fluvial system. There is an interplay between those aspects of drainage basins that do not change with time, and those variables that do.

For the purpose of predicting effects of climate change on the morphology of stream channels the model StreaMES (Stream Morphological Evaluation System) has been set up. Richards (1982) made a speculative representation of the alluvial channel system (Figure 4.2a). This conceptual model was implemented and adapted for the Dutch situation. The general scheme of the model StreaMES is given in Figure 4.2b. In the scheme the distinction is made between the exogenous factors (outside of the frame, at the top side) and the endogenous mechanisms

Figure 4.2a Richards conception of the alluvial channel system. Independent variables have heavy outlines; bed material size, though ultimately controlled by lithology, is semi-independent as it is effected by sediment transport. Direct relations are shown by +, inverse by -; arrows show direction of influence. Some links are reversible; as for example as friction.

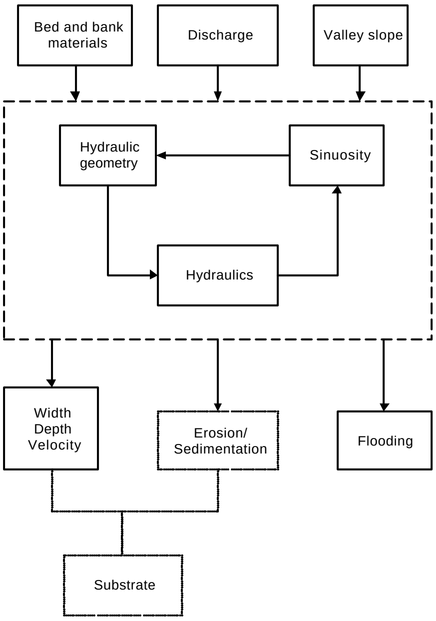


governing the channel system itself. The following exogenous factors are considered:

- substrate properties
- discharge
- valley slope

For the endogenous mechanisms free meandering of a stream is assumed. In the case study this is limited to the main arteries of the Reusel and Beerze. The model makes use of both physical and empirical relationships. In the following description the exogenous factors are illlustrated by data from the study region.

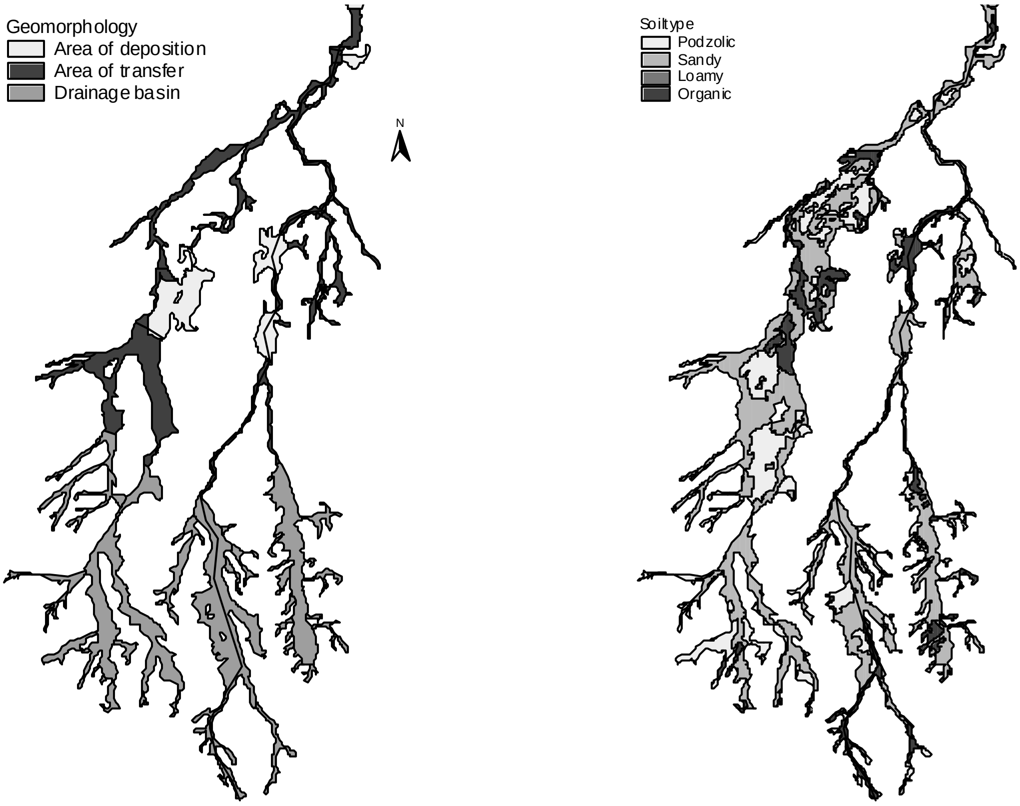
Figure 4.2b Outline of morphological prediction model StreaMES.



4.2 Exogenous factors

The (main) streams have been divided into a limited number of reaches, based on the geomorphology, soil and valley slope. The reaches provide the spatial resolution for attributing values of exogenous factors. Actual predictions for the channel reaches are, however, done for the (smaller) surface water subtrajectories of the regional hydrologic model SIMGRO. So a reach in StreaMES can cover more than one subtrajectory of the hydrologic model.

Figure 4.3 Geomorphological classification of main streams (left) and soil classification (right).



The first step is to make a subdivision based on the geomorphological map, which shows whether a reach belongs to the upper, middle, or lower reaches of a stream system (Figure 4.3, left). Then the reaches are further subdivided based on the soil map (Figure 4.3, right).

From Figure 4.3 it is apparent that the soil map closely correlates with the geomorphological map, and that most of the soils are sandy and podzolic. So at first glance it is not necessary to further subdivide the reaches using the soil map. However, the loam fraction of the soil does differ within the geomorphological classes, and is also an important factor for determining the erodibility of the substrate. So a further subdivision of reaches was based on the loam fraction.

In general the valleys of the main streams follow a smooth logarithmic profile. At a more detailed scale sharp changes in slope can be found. These sharp changes on a local scale appear to take place concurrently with changes in the soil characteristics. So the variation of the valley slope was not used for further subdividing the reaches. In total 16 reaches are distinguished for a total stream length of about 80 km (Reusel and Beerze).

The following parameters have been coupled to the substrate:

- the side-slope of the stream
- the hydraulic geometry
- the hydraulic conductivity

For the side-slope of the stream the empirical data given in Table 4.1 have been used (taken from Cultuurtechnisch Vademecum 1988). For the hydraulic geometry in relation to the substrate a distinction has been made between deep, medium deep, and shallow profiles. This distinction is based upon the stability of the soil layers. In Cultuurtechnisch Vademecum (1988) the following empirical relationships are given between the bottom width B and the depth of the cross-profile h:

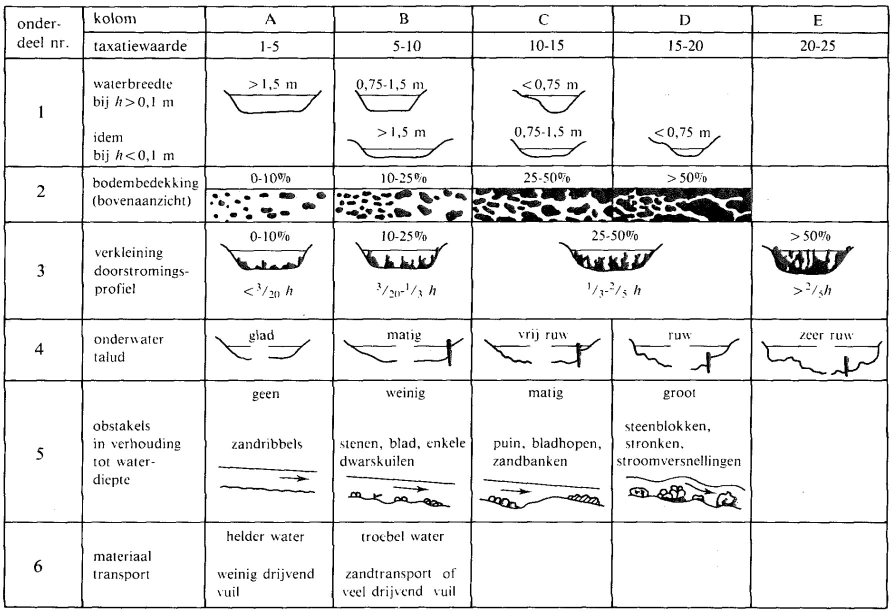
- $B = 2.00\ h^{5/4}$ for deep profiles (4.1a)
- $B = 2.75\ h^{3/2}$ for medium profiles (4.1b)
- $B = 5.00\ h^{5/2}$ for shallow profiles (4.1c)

The hydraulic conductivity is in this study quantified in terms of the Manning coefficent k_M. The k_M–value is very much determined by the amount of vegetation that is present in the waterway. A method developed by Bon (1967) has been used for classifying the streams in terms of their ‘degree of maintenance’. Determination of the degree of maintenance is done by using an estimation scheme (Figure 4.4). For six aspects, which have an influence on the hydraulic conductivity, a rating has been given. The average value of the six ratings is an indication for the degree of maintenance. For the streams in this study this is usually about ‘4’ on a scale from 1 (most maintenance) to 9 (least maintenance). Then the empirical information given in Cultuurtechnisch Vademecum (1988) was used for the relationship between the k_M and the mean stream velocity (Figure 4.5).

Table 4.1 Side-slope of stream, depending on soil type (Werkgroep Herziening Cultuurtechnisch Vademecum 1988).

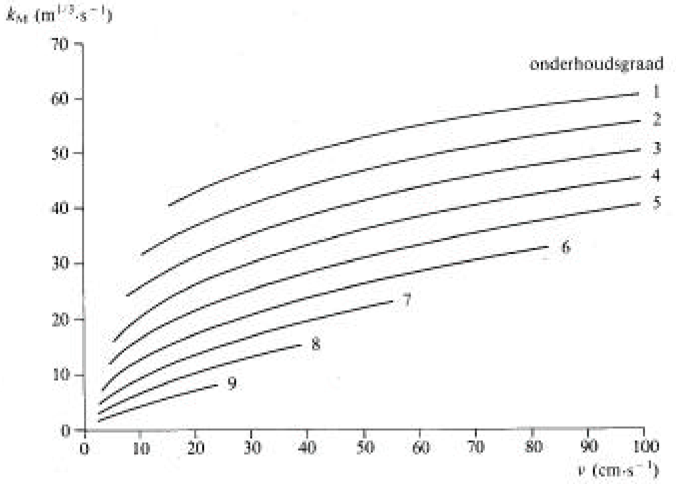
Soil type	Side-slope (width/height)
Clay, loam, loss, hard peat	1 – 2
Zavel, hard sand	1.5 – 2.5
Coarse sand	1.5 – 3
Fine sand, loose peat	2 – 4

Figure 4.4 Estimation scheme for the degree of maintenance.



onder-deel nr.	kolom	A	B	C	D	E
	taxatiewaarde	1-5	5-10	10-15	15-20	20-25
1	waterbreedte bij $h > 0{,}1$ m	> 1,5 m	0,75-1,5 m	< 0,75 m		
	idem bij $h < 0{,}1$ m		> 1,5 m	0,75-1,5 m	< 0,75 m	
2	bodembedekking (bovenaanzicht)	0-10%	10-25%	25-50%	> 50%	
3	verkleining doorstromings-profiel	0-10% $< {}^{3}/_{20}\ h$	10-25% ${}^{3}/_{20}$-${}^{1}/_{3}\ h$	25-50% ${}^{1}/_{3}$-${}^{2}/_{5}\ h$		> 50% $> {}^{2}/_{5}h$
4	onderwater talud	glad	matig	vrij ruw	ruw	zeer ruw
5	obstakels in verhouding tot water-diepte	geen zandribbels	weinig stenen, blad, enkele dwarskuilen	matig puin, bladhopen, zandbanken	groot steenblokken, stronken, stroomversnellingen	
6	materiaal transport	helder water weinig drijvend vuil	troebel water zandtransport of veel drijvend vuil			

Figure 4.5 Relationships between the Manning coefficient k_M for the hydraulic conductivity and the mean stream velocity, for varying degrees of maintenance (*onderhouds-graad*) of the stream (1 = most maintenance, 9 = least maintenance).



The so-called bank-full discharge is thought to determine the stream profile, as is generally assumed. Richards (1982) defines the bank-full discharge as the discharge with a mean recurrence interval of 1.6 years. The regional hydrologic model supplies these discharges for each of the surface water subtrajectories.

The mean valley slopes of the surface water subtrajectories have been determined using a Digital Terrain Model (DTM) of the study region.

4.3 Endogenous system relationships

For the flow resistance the Manning-equation for steady state flow in a conduit has been used:

$$Q_{bf} = k_M \; A \, R^{2/3} \sqrt{S_b} \tag{4.2}$$

in which:

- Q_{bf} : bank-full discharge (m^3/s)
- k_M : Manning coefficient ($m^{1/3}$/s)
- A : wetted cross section (m^2)
- R : hydraulic radius (m)
- S_b : gradient along the stream bed (-)

The hydraulic radius is the wetted cross section divided by the wetted perimeter.

The second system relationship concerns the sinuosity of the stream. The sinuosity is the ratio between the length of the stream and the distance ('as the crow flies') along the valley bottom: the higher the value, the more the stream meanders. The sinuosity mainly depends on the soil material, the valley slope and the width/depth ratio of the stream. The following relationship given by Chitale(1970) has been used:

$$x = 1.429 \left(\frac{D_{50}}{h}\right)^{0.077} S_v^{-0.052} \left(\frac{W_{top}}{h}\right)^{-0.065} \tag{4.3}$$

in which:

- ξ : sinuosity (-)
- D_{50} : median grain size of substrate (m)
- S_v : valley slope (-)
- W_{top} : width of stream at the top of the cross-profile (m)
- h : water depth (m)

4.4 Calculation method

There are three unknown parameters in the equations:

- the bottom width B
- the water depth h
- the sinuosity ξ

The width W_{top} at the top of the profile is also an unknown parameter, but it follows directly from the bottom width B, the side-slope (Table 4.1) and the water depth. And the slope along the streambed S_b is equal to the valley slope S_v divided by the sinuosity ?. For the remaining three unknowns given above there are also three equations, so a solution can be found. For finding the solution an iterative procedure has been programmed and linked to a spreadsheet. The model was used to calculate the hydraulic geometry and sinuosity of the subtrajectories of the streams. Changes in the hydraulic geometry and sinuosity will result in changes in stream length, stream slope, stream depth and storage in the SIMGRO-model. By re-running the SIMGRO model a number of times, each time with an update of the channel dimensions, the equilibrium state of the channel geometry can be obtained.

5 COUPLING OF HYDROLOGICAL TO ECOLOGICAL MODELS

P.E.V. van Walsum, P.C. Jansen , F.J.E van der Bolt, & A.A. Veldhuizen

5.1 Introduction

For use as input to ecological submodels the raw output data of the regional model SIMGRO have to be postprocessed. This postprocessing is necessary for a variety of reasons, involving:

- downscaling of watertables to the appropriate spatial scale
- explicitation of the ecologically relevant upward seepage flux
- computation of the moisture stress
- computation of discharge statistics

The developed procedures are described in Sections 5.2 through 5.5

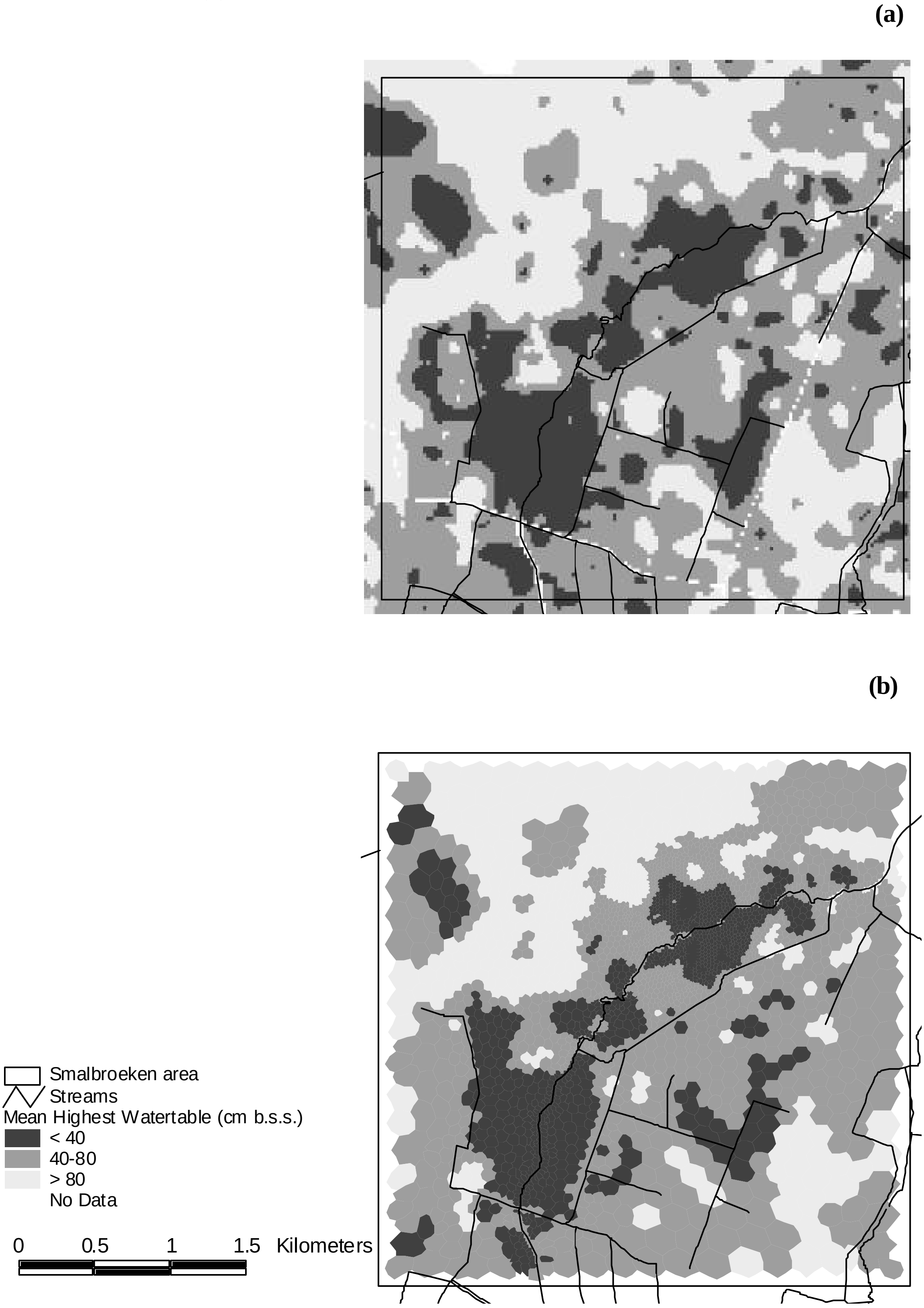
5.2 Downscaling of watertables

The NATLES evaluation model (Section 7) for the terrestrial ecology uses a 25 x 25 m grid. In order to do justice to that fine spatial scale the watertables computed by SIMGRO have to be downscaled from the values for the nodal subdomains that have a cross-section of at least 100 m, and a mean diameter of 240 m. The employed downscaling method is based on the notion that at the scale of 25-100 m the topography is the determining factor for the local variations of the watertable depth with respect to the soil surface. Thus the procedure involves the following steps:

- the watertables for the nodal subdomains are considered to be point values at the nodal points of the finite-element network
- using the GIS-software ArcInfo a spline surface is interpolated between the watertables at the nodal points, and then converted to the 25 x 25 m grid
- the obtained watertables are subtracted from the Digital Terrain Model of the region, that also has a grid with 25 x 25 m

This method has been verified by making a so-called zoom model for a 3.5 x 3.5 km block in the ‘Smalbroeken’ area (for the location see Figure 1.2). The mean diameter of the 3000 nodal subdomains is 60 m. As can be seen from the comparison made in Figure 5.1 for the current situation, the verification shows that the downscaling procedure works well.

Figure 5.1 Simulated maps of Mean Highest Waterable in the Smalbroeken area: simulated with the model for the whole region, then downscaled (a) and simulated with the zoom-model (b).

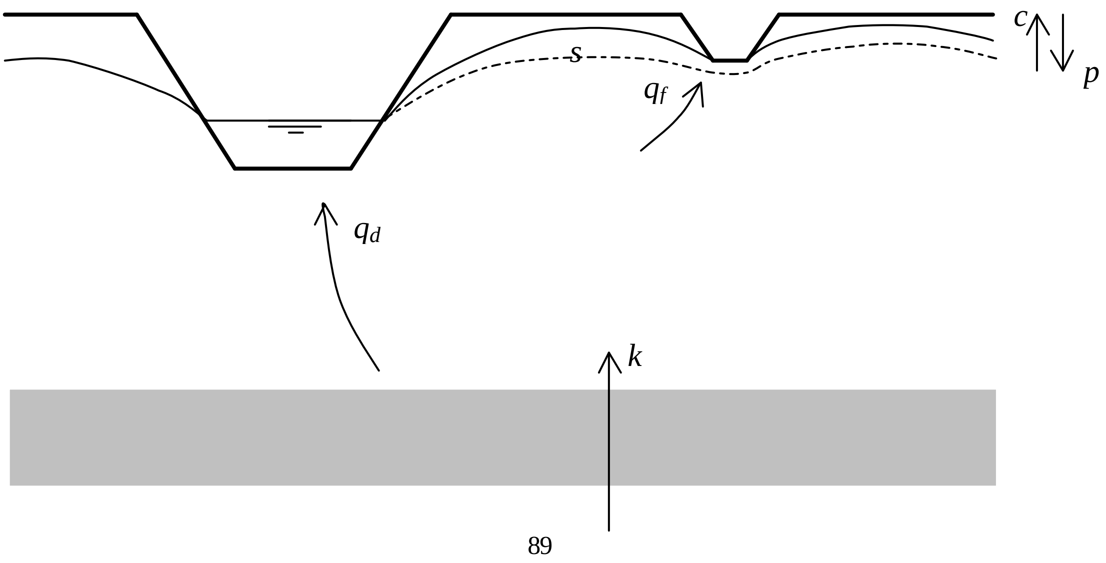


5.3 Seepage to the rootzone

For the ecological evaluation with NATLES we need to know the *gross upward seepage flux to the root zone,* because this flux determines to what extent the sites are buffered against acidification. The buffering substance is the bicarbonate contained in the groundwater. The mentioned flux is not the same as the gross seepage flux passing through the bottom of the first aquifer, because most of that water directly flows into the deeper ditches and does not reach the root zone at all. The mechanism at play involves the build-up of a precipitation lense on top of the groundwater that seeps up from the deeper aquifer (area enclosed by watertable and dotted line in Figure 5.2). This lense is thickest in winter and becomes thinner during the summer half-year. Only when the lense completely vanishes does the seepage reach the root zone. For an accurate calculation of the amount of water that actually reaches the root zone it would be necessary to use a fully three-dimensional model of groundwater flow and not a so-called quasi-3D model that is used here. But that is not all, because it would also require the modelling of every deep ditch in an explicit manner, and without any ‘lumping’ that inherently is done by using the concept of a drainage resistance based on the average density of conduits forming the drainage system.

In this study a simplified approach is followed, that aims at making an upper bound estimate of the gross seepage to the root zone. Such a *max*-estimate is perhaps less accurate than a method that aims at a ‘best’ estimate, but has the advantage that one can say more about the

Figure 5.2 Schematisation for calculation of the gross upward seepage flux to the root zone. The precipitation lense with storage volume s_t has to vanish before any seepage to the root zone can take place.



uncertainty interval: in the case of the *max*-estimate, the (unknown) real value is clearly not higher. In the case of a ‘best’-estimate nothing at all can be said about the uncertainty interval (unless of course the results are compared to a study involving every single ditch in the model). In the approach described here the assumption is made that *as long as there is water in the precipitation lense and at the same time there is drainage to ditches, the drainage water will purely consist of precipitation water stored in the lense*. In reality some of the drainage water to ditches will consist of deep seepage water long before the precipitation lense has completely vanished. So the lense will exist longer than is predicted in the simplified approach, and thus the seepage to the root zone will in reality be less than what is calculated.

The implementation of the method involves making a day-to-day water balance of the water in the precipitation lense:

$$s_t = s_{t-Dt} + (p_t - c_t - \Sigma_\mathrm{i}\, q_{i,t})\cdot \Delta t \tag{5.1}$$

in which:

- s_t : volume of water in the precipitation lense at time t (m)
- p_t : percolation from the root zone to the watertable (m/d)
- c_t : capillary rise from the watertable to the root zone (m/d)
- $q_{i,t}$: drainage flux to i^{th} order of drainage media (m/d)
- Δt : time interval of 0.25 day (d)

If the computed value drops below zero, the storage is set to zero. Seepage to the root zone is only computed for periods with $s_t = 0$. That seepage is set equal to the net capillary rise plus the flux to the shallow trenches:

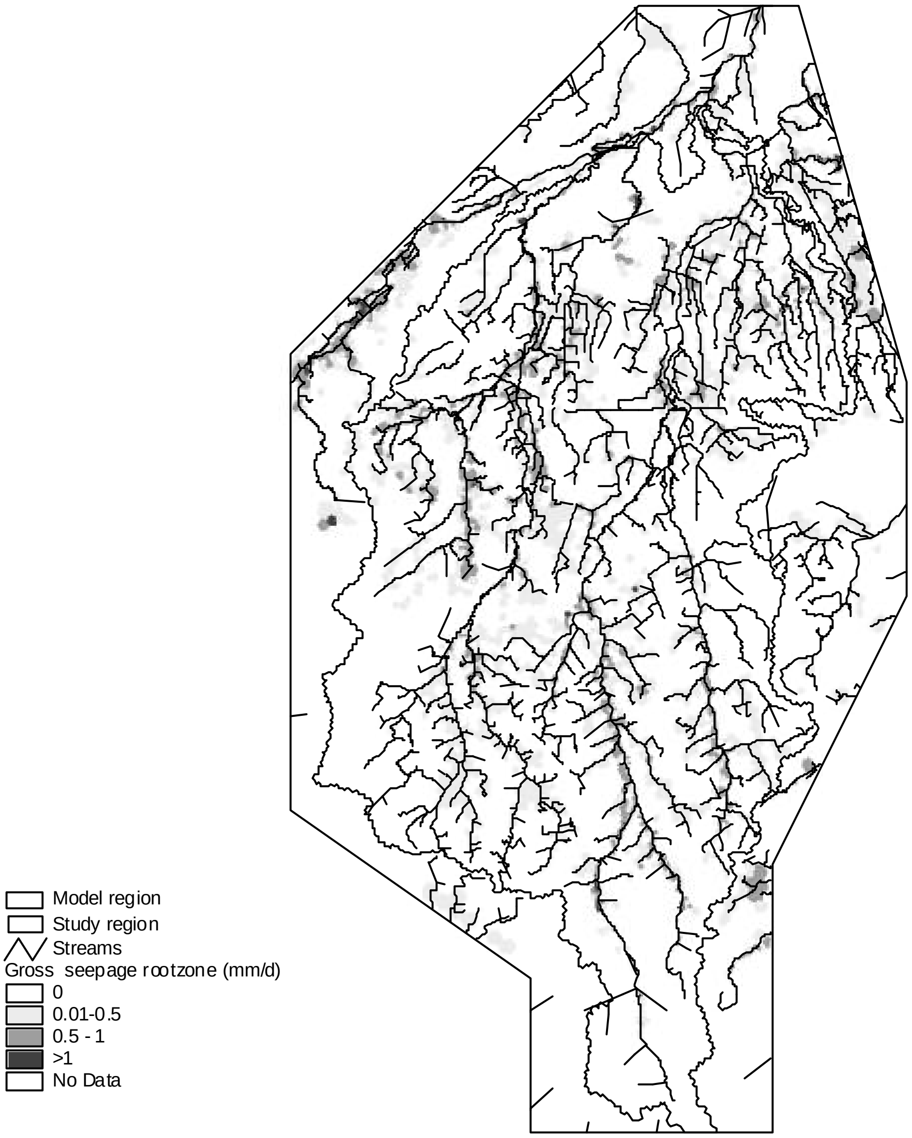
$$w_t = w_{t-?t} + \mathbf{max}\ \{0, (c_t - p_t + q_{f,t})\cdot \Delta t\ \} \tag{5.2}$$

in which

- w_t : the gross upward seepage to the root zone at time t (m)
- $q_{f,t}$: drainage flux to shallow trenches (m/d)

The max-operator is to ensure that only positive contributions are counted. The reason for including the flux to small trenches is that this water out of necessity passes near to the roots

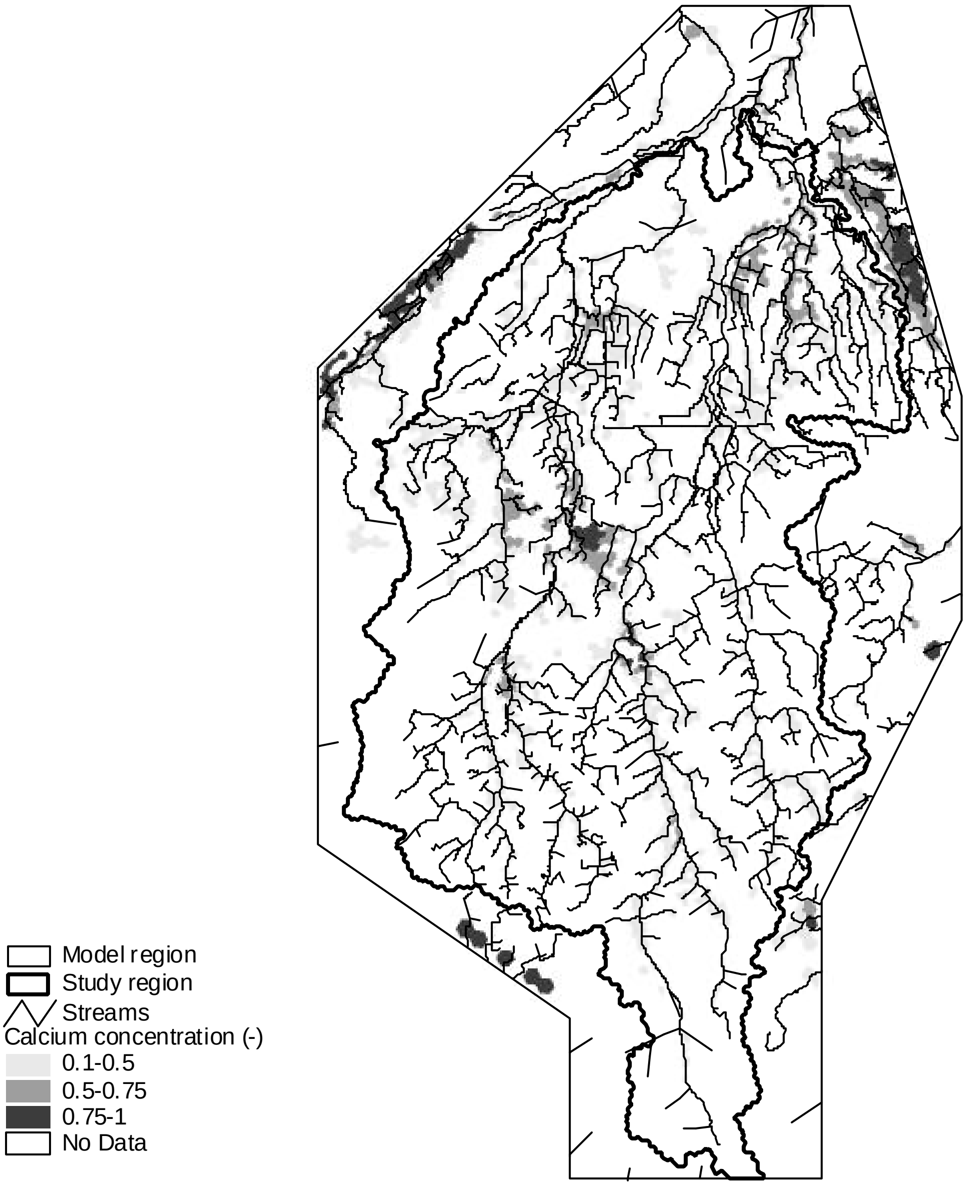
Figure 5.3 Gross upward seepage to the root zone (maximum value estimate), computed for the current situation.



of plants, because the trenches are shallow and more evenly distributed than the ditches. The computed seepage for the current situation is given in Figure 5.3.

Another reason for the overestimation of the seepage to the rootzone is that in the balance given in Eq. 5.1 no distinction is made between the saturated and the unsaturated zone: the balance is made for the total system volume including both zones, starting from the bottom boundary of the precipitation lense and ending at the bottom of the root zone. This means that according to the balance equation drainage of water to ditches can effectively ‘remove’ *all* of the water in the unsaturated zone, whereas in reality that only holds true for the water that will freely drain from the soil under the force of gravity. Removal of the water that does not drain under gravity forces is only possible by flushing the system from below by seepage that drains through the trenches or from above by sucking water through the zone in the form of capillary rise. In many instances one of these mechanisms will indeed be active. And since the unsaturated zone is relatively thin in the wet stream valleys, the error made by this type of overestimation will not be very substantial.

Figure 5.4 Computed calcium concentrations of seepage water (that reaches the root zone), presented as a fraction of the saturated concentration



For the ecological evaluation not only the amount of seepage is relevant, but also the calcium content of the seepage water. Calcium enrichment of groundwater takes place during contact with calciferous sediments in the deep subsoil. We have assumed that the calcium solution process is governed by a first order differential equation of the form:

$$\frac{dc}{dt} = \frac{1}{T} \cdot (1 - c) \tag{5.3}$$

in which:

- c : dimensionless concentration, as a fraction of the saturated concentration (-)
- t : time (y)
- T : characteristic time of the solution process (y)

This equation is of course a simplification of reality, but suffices for obtaining an idea of the sensitivity for the various climate scenarios. The above equation has been implemented for the discretisation of nodal subdomains, for the 15 layers of the subsoil. A mixing-cell approach (semi-implicit for the time discretisation) has been used for the calculation scheme, assuming perfect mixing per time step of one year. For computing the end-concentrations such an approach provides satisfactory results, and that is all that is required in this study. The computed concentrations are given in Figure 5.4. The high concentrations just left to the center of the region are caused by deep groundwater that is forced to the surface by the Feldbiss fault that cuts right across the center of the study region from East to West.

5.4 Moisture stress of natural vegetation

5.4.1 Introduction

For evaluating the effects of climate scenarios on the natural terrestrial vegetation it is necessary to quantify the relationship between the climax vegetation and the soil moisture conditions. For very moist and moist conditions there is a high correlation between vegetations consisting of hygrophytes and mesophytes and the Mean Spring Watertable. (Runhaar *et al*. 1997). (The Mean Spring Watertable MSW is here defined as the average watertable in March-April) Hygrophytes are adapted to wet and periodically anaerobic circumstances. Mesophytes, however, need less moist conditions, but can not survive under extremely dry conditions (Londo 1975). Xerophytes are adapted to dry conditions, and their presence is well correlated to the so-called moisture stress (Jansen *et al*. 2000). The moisture stress is defined as the number of days (on average) that the pressure head in the rootzone is lower than –12 m. The relationship that has been found is:

$$Y = 0.38 \cdot X + 13.11 \qquad (5.4)$$

in which:

- X : percentage of xerophytes according to the moisture classification of species by Runhaar (1987) (%)
- Y : mean number of days with a pressure head < -12 m in the middle of the root zone (d)

In the standard version of NATLES (version 1.2) the moisture stress is related to the Mean Lowest Watertable. In that relationship the current climate is implicitly included in the coefficients. That means that the relationship is not suitable for use in a study involving impacts of climate *change*. So for this study we had to follow a different approach.

The SIMGRO model computes moisture contents that can be translated to pressure heads if required. However, these heads are only available at the scale of nodal subdomains. For interpolation to the pixels of 25 x 25 m needed for the ecological evaluation, the moisture contents are not very suitable. But the downscaling of watertables has proven to be a viable option (Section 5.2). For this reason we have sought relationships that make use of available watertables per 25 x 25 m in combination with the meteorological conditions.

5.4.2 Moisture stress as a function of watertable conditions and weather

The computational experiments for deriving the relationships were performed with the model SWAP (Van Dam *et al.* 1997). These experiments were done for soils classified according to the loam fraction, the coarseness, and the thickness of the top soil (A-layer). The soil physical data for the used series of soil profiles were taken from Wösten *et al.* (1994). The saturated moisture contents of the soil units have, however, been reduced by 20%, to account for processes like delayed rewetting (Van Walsum, pers. comm.). The choice of regression variables for deriving the relationships was based on physical notions about what can cause the dry conditions needed for letting the pressure head in the root zone drop below –12 m. The main notion is that extremely dry conditions can only prevail if the following two conditions are met:

- there is a limited supply of water from below, involving limited capillary rise from the watertable
- there is a large demand of water from above, involving a prolonged period with a precipitation deficit

For quantifying the limitation of supply from the watertable the soil physical characteristics have been analyzed with a steady-state version of SWAP. The watertable depth has been determined that allows a maximum capillary rise of 0.5 mm/d. This depth is here called the z-level. For coarse sandy soils a value of about 80 cm b.s.s. is found, for sandy soils with high loam content the z-level is around 250 cm b.s.s. The notion behind the choice of 0.5 mm/d is that for higher values the drying out of the profile is not likely, whereas for lower values it becomes possible. For estimating the limitation of supply from below the longest *continuous* period that the watertable drops below the z-level is determined. This is done for each year of the simulation period.

For quantifying the limitation of water supply from above a day-to-day cumulative balance of the precipitation deficit is made:

$$d_t = d_{t-1} + E_t - P_t \tag{5.5}$$

in which:

- d_t : cumulative precipitation deficit at time t (mm)
- E_t : potential evapotranspiration on day t (mm)
- P_t : precipitation on day t (mm)

For each year of the simulation period the maximum value of the cumulative deficit is determined.

Various regression models were tried for fitting to the data of the experiments with SWAP. In the end the following model was found to give the most satisfactory results for relating the moisture stress X to the regression variables:

$$X = c_1 T_z + c_2 D + c_3 T_z D \tag{5.6}$$

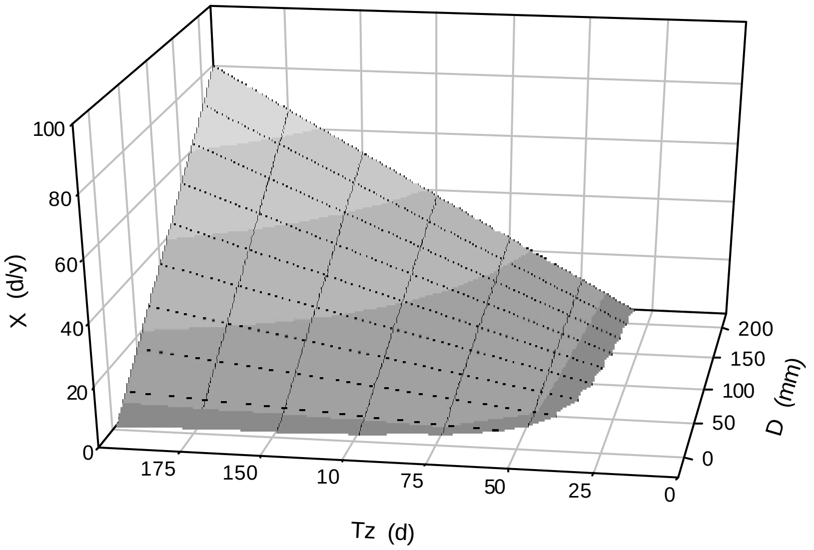
in which

- X : number of days that the pressure head in the root zone drops below –12 m (d/y)

- T_z. : number of consecutive days with the watertable below the z-level (d)
- D : maximum cumulative precipitation deficit (mm)
- c_1, c_2, c_3 - regression coefficients

The hyperbolic term (c_3T_zD) is crucial because it models the interplay between the two factors involved: moisture stress develops if water supply from below and from above are both limiting in the *same* year. For loamy sand the explained variance is only 50%, but for the rest the explained variance is 85-90%. In Figure 5.5 an example is given of the regression function.

Figure 5.5 Example of a regression function for the moisture stress (X) as a function of:
- T_z. : number of consecutive days with the watertable below the z-level (d)
- D : maximum cumulative precipitation deficit (mm)



5.4.3 Application on a regional scale

For application on a regional scale the watertable results of the SIMGRO-model are interpolated from the nodal points to the 25 x 25 m pixels for each time step of the simulation, the same way as for downscaling of the watertables using ArcInfo in Section 5.2 But since the procedure had to be repeated more than 5 000 times per simulation run of 30 years (summer half years), a FORTRAN-program was written to speed up the computation process. The regression formula (Eq. 5.6) was applied for each pixel and each year *separately*, and then the values were averaged. The results for the current situation in the study region are presented in Figure 5.6.

Figure 5.6 Simulated moisture stress for the current situation.

5.5 Discharge statistics for aquatic ecology

For making the aquatic-ecological evaluation of the scenarios a number of discharge statistics are computed involving the median discharge. These statistics have been chosen with a view to quantifying the variability of the discharge, with special attention paid to the extremes at the low and high end of the discharge spectrum. The lower and upper bounds of the classes are defined in terms of a factor times the median discharge Q_{50}.

Table 5.1 Discharge extremity classes for evaluating the variability of the discharge. The lower and upper bounds are defined in terms of a factor times the median discharge Q_{50}. Per class the percentage of discharges is determined that falls within the interval defined by the lower and upper bounds

Discharge extremity class	Lower bound of discharge class (-)	Upper bound of discharge class (-)
O5	16.00	*8*
O4	8.00	16.00
O3	4.00	8.00
O2	2.00	4.00
O1	1.00	2.00
U1	0.90	1.00
U2	0.70	0.90
U3	0.30	0.70
U4	0.05	0.30
U5	0.00	0.05

By way of example, the class O_3 is graphically illustrated in Fig. 5.7. O_3 is the percentage of discharges in the interval:

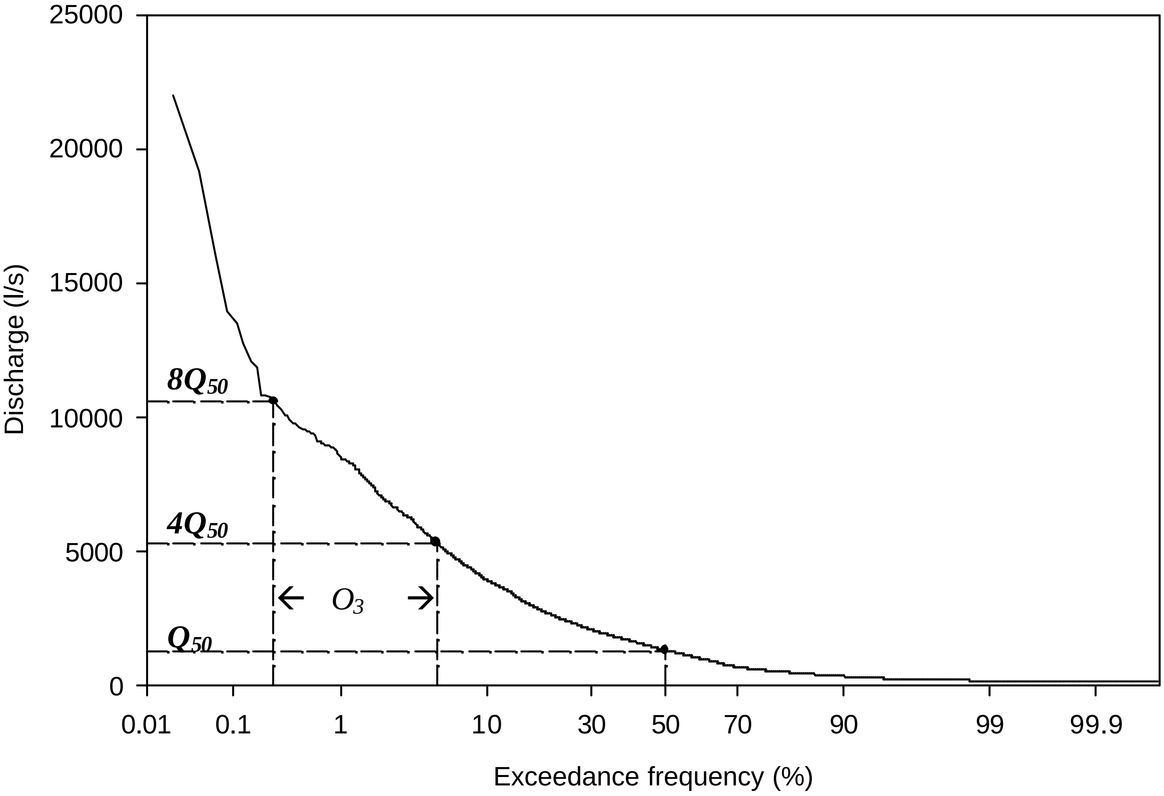
$$4\,Q_{50} < Q < 8\,Q_{50} \qquad \text{(interval } O_3\text{)}$$

In some instances the values are in the text given in [days/year] which corresponds to 0.274%.

In terms of extremes the aggregated parameters are used:

$$R_i = U_i + O_i \quad , \quad \text{for } i\text{=1....5} \tag{5.8}$$

Figure 5.7 Graphical illustration of the discharge extremity class O_3. O_3 is the percentage of discharges between 4 and 8 times the median discharge Q_{50}.



6 AQUATIC ECOLOGY OF LOWLAND STREAMS

P.F.M. Verdonschot, M.W. van den Hoorn & Tj.H. van den Hoek

6.1 Introduction

A stream is a dynamic but balanced environment (Huston 1979, Minshall 1988). Macro-invertebrates are seen as indicator species, and therefore they are used for making predictions for the impacts of climate change. Since the beginning of this century, lotic ecologists have assumed that the shapes of benthic macro-invertebrates in running waters resulted from natural selection to minimize the forces of flow that act on them. For a long time it was commonly accepted that the benthos lives in the boundary layer at the substratum surface, and is rather protected from the flow. More recently it has been shown that streamlined or dorsoventrally flattened animals experience rather complicated flows and consequently endure the forces of flow (Statzner et al. 1988).

Flow also stirs a species environment, it delivers nutrients and food particles and removes wastes and allelochemicals. It also removes macro-invertebrates. Flow characteristics are probably the most important actors in a stream ecosystem development. Every stream endures flow. But flow can be constant or varying. Most effects on the stream community are a consequence of low or high flow events. The intensity, frequency, and severity of such flow events determine the stability of the stream bed and thus of the macro-invertebrate habitat (Resh et al. 1988). Furthermore, Resh et al. assume that predictability of hydrologic regime is important with respect to ecological phenomena. The more predictable a flow regime will be, the more the biotic community will be adapted to it (Horwitz 1978). In this study predictability of flow was not included; we assume that our lowland-streams flow-regime is always unpredictable. The response of the macro-invertebrates to extreme flow events and their ability to recover are expected to be related to the discharge regime.

Meeting the general approach for predicting effects of climate change as outlined in Section 1, a distinction is made between the direct and indirect effects of climate change. Direct effects apply to the effects of temperature and indirect effects to the changes of the hydrology and of the stream bed acting as a substrate for the macro-invertebrates. This chapter describes how hydrology and substrates act as determinants of macro-invertebrate distribution in lowland streams. The effects of temperature are discussed in Chapter 10, along with the effects of temperature on terrestrial ecosystems.

6.2 Hydrology and substrates

In making predictions for indirect effects through hydrology and substrates we face the problem that the impact of climate change and of most human activities are at the scale of the drainage basin, whereas the effects on the in-stream habitats of macro-invertebrates are at the scale of square centimeters on the stream bed. The complexity of flow, substrates and communities is such that an accurate prediction is a step too far, especially if attempted at the scale of the habitat. But the distribution of macro-invertebrates in a stream is surely not coincidental. An ecologist standing at the bank of a stream is able to name several species present without have seen them.

Already more then ten years ago Statzner *et al.* (1988) pointed out that discharge and substrate are not enough to characterize the physical habitat of a stream. The question rises which parameters are necessary to tell the ecologist which species will be present. The discharge of a stream shapes the substrates (Verdonschot *et al.* 1998) and both together compose the habitat of the macro-invertebrates. In this study a number of relatively simple parameters acting at different scales are included and related to the macro-invertebrate distribution patterns in streams and in-stream habitats. The main question posed is: “How does discharge interact with stream substrates and how do the macro-invertebrates fit in?” For answering that question research has been conducted at ten field sites, each in a different stream with a different discharge regime.

6.3 Study sites

The ten studied streams all are soft-bottomed, lowland streams with a slope of about 0.5 - 5 m/km. They are located in the eastern and southern parts of the Netherlands. The streams are representative for upper and middle courses of natural lowland streams. All streams are near-natural and represent different hydrological regimes. The ten soft-bottomed lowland streams were selected based on the following criteria:

- the streams are not disturbed by human activities (near-natural)
- they have a near-natural morphology and water chemistry
- they represent different hydrological regimes

Based on these criteria the ten streams are categorized into so-called stream types (Verdonschot 1994), as indicated in Table 6.1.

The Netherlands has a temperate climate with a precipitation surplus of about 300 mm per year. Stream temperatures range between 0 and 18 ^{o}C. The streams are either fed by rainwater or by helocrene springs. In both types direct runoff is important too. The streams range between 0.5 and 4.0 m in width. The stream velocities range from 0 to more than 60 cm/s,

Table 6.1 Categorization of the ten studied streams into types (see also Verdonschot, 1994).

Code	Stream name	Stream type
BB	Forest stream	natural organic small upper course
FB	Frederik-Bernhard stream	natural spring-fed sandy upper course
KB	Cold stream	natural spring-fed sandy upper course
OB	Old stream	natural spring-fed sandy upper course
RB	Red stream	natural sandy middle course
RE	Reusel	semi-natural sandy middle course
RO	Rosep	semi-natural sandy middle course
SN	Springendael stream North	natural spring-fed sandy small upper course
SZ	Springendael stream South	semi-natural spring-fed sandy small upper course
TB	Tongerense stream	semi-natural spring-fed sandy upper course

Table 6.2 General physico-chemical characteristics of the ten streams studied (stream; codes are explained in Table 6.1, av. = average value, n = number of samples).

stream	SN		SZ		RO		RE		RB		BB		TB		OB		KB		FB	
	av.	n	av.	n	av.	n	av.	n	av.	n	av.	n	av.	n	av.	n	av.	n	av.	n
Ca [mg/l]	16.2	32	18.2	29	42.7	4	49.7	6	32.4	9	13.3	8	17.0	9	18.8	9				
Cl [mg/l]	25.3	57	20.4	54	23.3	73	34.8	88	27.5	10	11.1	8	10.1	9	15.9	9	20.9	12	22.3	59
CO_3 [mg/l]	1.1	32	1.0	29	2.0	1	3.0	2					2.0	9	2.0	9				
Fe^{2+} [mg/l]	0.02	19	0.04	17	2.20	5	2.08	5					0.01	9	0.01	9				
Total hardness	0.61	17	0.64	14	0.86	1		0					0.51	9	0.59	9				
HCO_3 [mg/l]	12.5	32	16.0	29	98.5	4	38.0	5	56.5	9	9.00	8	43.2	9	25.6	9				
EC	221	56	216	54	315	3	510	6	323	9	126	8	131	9	174	9	244	12	286	57
K [mg/l]	4.6	56	6.6	53	8.0	16	16.9	19	5.4	9	1.5	8	1.7	9	2.6	9			9.9	4
Mg [mg/l]	8.3	32	6.3	29	4.7	1	12.5	7	5.2	9	1.6	8	2.0	9	3.0	9			4.6	4
Kj-N [mg/l]	0.53	57	0.84	54	1.30	38	1.77	41	2.16	9	1.00	8	0.91	9	0.85	9	0.99	12	1.56	59
Na [mg/l]	14.9	32	11.4	29	16.3	4	22.6	7	18.0	9	5.85	8	6.80	9	9.94	9			11.0	4
NH_4-N [mg/l]	0.10	57	0.11	54	0.24	107	0.50	123	2.10	10	0.34	8	0.04	9	0.04	9	0.08	12	0.25	46
NO_2-N [mg/l]	0.01	57	0.01	54	0.04	95	0.06	95	0.14	10	0.15	8	0.00	9	0.01	9	0.01	12	0.05	50
NO_3-N [mg/l]	10.3	57	9.11	54	3.27	95	8.78	95	1.34	10	0.43	8	0.62	9	5.85	9	5.68	12	5.20	59
o-P [mg/l]	0.03	56	0.04	54	0.20	1	0.09	4	0.07	10	0.05	8	0.02	9	0.02	9	0.02	12	0.09	45
total-P [mg/l]	0.07	57	0.12	54	0.83	1	0.09	117	0.24	10	0.10	8	0.08	9	0.07	9	0.07	12	0.19	55
SO_4 [mg/l]	27.0	57	33.8	54	32.7	107	101	123	49.1	10	33.1	8	14.8	9	17.0	9	29.3	12	29.7	59
pH [--]	6.4	55	6.6	53	7.3	107	6.6	119	7.6	10	7.0	8	7.3	9	6.9	9	7.3	12		

with an average of 20-30 cm/s. The depths range from 0-50 cm, and are on average about 10 cm. The streambeds are very diverse, each with their own mosaic of substrate types. The most important physico-chemical parameters are given in Table 6.2.

6.3 Material and methods

Hydrology

The streams were studied from July 1997 until October 1998, over a 15-month period. Discharge was recorded continuously, through registrations of the water level at 15-minute intervals. One stream appeared to have too few reliable data for being included in the analysis. Discharge data of the one available hydrological year were summarized into various groups of hydrological parameters to test the relevance for the macro-invertebrate community. The respective groups concern stream and temporal discharge characteristics, stream and temporal discharge dynamics, normal and extreme discharge events and cumulative discharge. In one method the discharge series of the studied streams were characterised by frequency curves for discharge. Of special interest for the predictions made in this study are also the specific low- and high-end discharge-extremity intervals defined in Section 5.5. These intervals are defined in relation to the 50% percentile, the median flow Q_{50}. The median flow is also used as estimation for the base flow. Base flow was also calculated separately for the summer and winter half-year. The ratio between the two indicates the importance of groundwater seepage: the lower the summer value compared to the winter one, the lesser the role of groundwater seepage.

Substratum

In each fifth week the cover percentages of major substrates were estimated over a stretch of 30 meters in each stream during the study period. This field estimation was done per stretch of two meters. So, for each site fifteen stretches were estimated. From the major substrate types also samples for measurement of grain size and organic matter content were taken.

Macro-invertebrates

Macro-invertebrates were sampled 3 times in all ten streams in autumn (1997), spring (1998) and autumn (1998). The samples were taken by means of a micro-macrofauna-shovel of 10 by

15 cm (so the sampled surface area is 150 cm^2). At each site the five major substrate types were sampled, sorted and preserved in alcohol (70% dilution), except for oligochaetes and watermites which were preserved in formalin (4% dilution) and Koenike fluid, respectively. All macro-invertebrates were identified down to species level, if possible.

Data processing

All data were analyzed by means of statistical techniques. The macro-invertebrate data were analyzed by multivariate analysis on habitat and stream level. The analyses of the relation between macro-invertebrates and environmental parameters was done by ordination analysis using the program CANOCO, option DCCA (Detrended Canonical Correspondence Analysis, Ter Braak 1989). DCCA is an ordination technique based on reciprocal averaging which results in an ordination diagram.

Environmental variables were selected on the basis of the inter-set correlation with the axes (correlation coefficient > 0.4: the correlation between a variable and an ordination axis). All variables selected by this procedure indicate important environmental gradients. For each ordination, the sites or habitat samples and the selected environmental variables were represented in the DCCA ordination diagrams. An environmental variable (indicated as an arrow in the diagram) points approximately in the direction of the steepest increase of that variable across the diagram; the length of the arrow is equal to the rate of change in that direction. This means that the value of an important environmental variable to a macro-invertebrate taxon is visualised by its perpendicular projection on the environmental arrow or its imaginary extension (in both directions).

Some other parameters of an ordination are of interest. The eigenvalue ranges between zero and unity and can be considered as a measure of between-site variability or beta-diversity. The eigenvalues of the individual axes are regarded as a measure of their relative importance within one analysis. The species-environment correlation coefficient measures the strength of the relation between species and the environment for a particular axis. The percentage of variance of the species-abundance data accounted for by the species-site biplot indicates the goodness of fit of the diagram with respect to the distribution of species abundance. The percentage of variance of the species-environment data in the species-environment biplot indicates the goodness of fit of the environmental variables. These parameters never reach 100% because of noise in the data and are always relatively low in large data sets. The total inertia is the total variance in the species data as measured by the chi-square of the sample-by-species table divided by the tables-total.

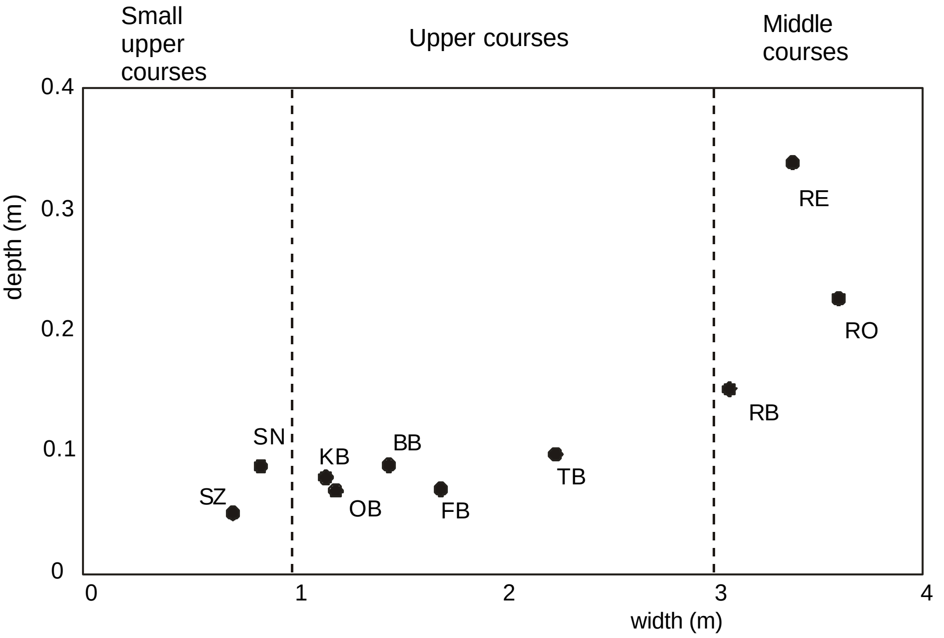
The distribution of the macro-invertebrate taxa over the different substrate types was calculated by using the index of representation IR (Hildrew & Townsend 1978) and the statistical significance of this index was tested by using a chi-square test (e.g. Lindgren & McElrath 1970). The index of representation supposes under the null hypothesis that a taxon occurs in all substrate types in equal densities. The null hypothesis is accepted when the difference between observed and expected densities is too small to reach chi-square values higher then the 5% significance level. Only in cases where the null hypothesis is rejected and the index shows an over-representation (positive IR with a value > 4) a taxon shows a preference for a substrate type.

6.4 Results

Stream type

Classification of streams into so-called stream types (Verdonschot 1994) is very useful for obtaining a better understanding of stream ecology. The type summarizes the key ecosystem characteristics into groups in this study, for small upper courses, upper courses and middle courses. Each group has a certain internal homogeneity of ecological key features and the

Figure 6.1 The studied streams typified by the width-depth relationship.



systems within a group function in a comparable way. A very simple technique to define stream types is to plot the width against the depth. There is an increase in wet cross-profile area (Figure 6.1) whereby two small upper courses (SN, SZ), five upper courses (KB, OB, BB, FB, TB) and three middle courses (RB, RE, RO) of lowland streams are distinguished.

Hydrology

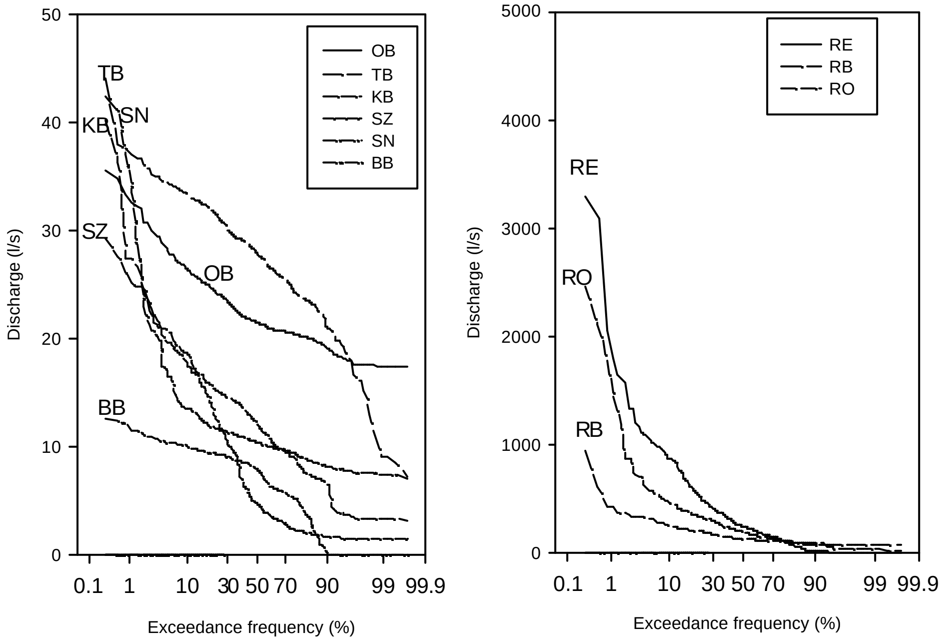
To compare the hydrology of all nine streams (the data of the tenth were not reliable), exceedance frequency curves (expressed in %) for discharges were plotted (Figure 6.2). A line that intersects (or nearly intersects) the horizontal axis indicates a stream with no (or low) discharge in summer, a so-called intermittent stream. The Forest stream (BB) is such an example. If a line is steep at the left, thus shows high discharges at low exceedance frequencies, then such stream has a flashy regime at moments of high discharge. An example of such a regime is shown by the Reusel (RE). Based on the exceedance frequency curves there are three (OB, BB, SN), three intermediate (RB, KB, TB) and three flashy streams (RE, RO, SZ) in the studied set.

The analysis of the base-flow ratio (Q_{50} of summer divided by Q_{50} of winter) yielded the values given in Table 6.3. Four hydrological stream types are distinguished. A group of stream types that are constantly fed by groundwater within a drainage basin having a high retention capacity consists of RB, OB, SN and TB. Springendal stream south (SZ) is intermediate. The summer flow regimes of KB, BB and RO are partly dependent on precipitation events in summer, while the flow regime of RE is almost completely determined by the precipitation in summer.

Table 6.3 Baseflow ratios ($Q_{50,summer}$/ $Q_{50,winter}$) of the studied streams.

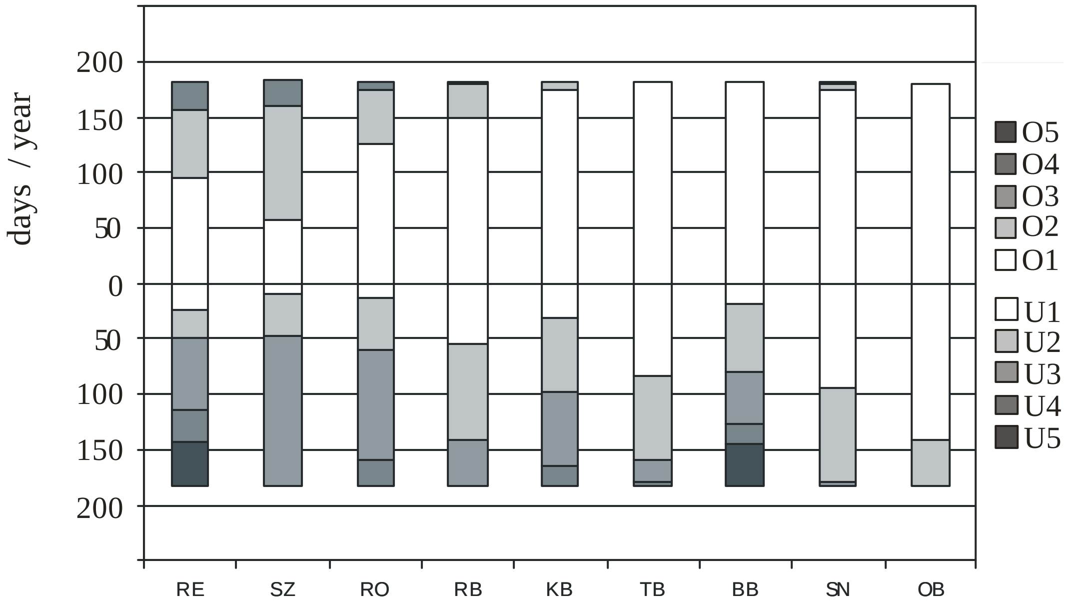
Stream	RB	OB	SN	TB	SZ	KB	BB	RO	RE
Baseflow ratio(-)	0.968	0.942	0.919	0.913	0.818	0.605	0.588	0.545	0.379

Figure 6.2 Exceedance frequency curves for discharges of the nine studied streams.



Of the different groups of hydrological parameters the discharge dynamics seem to be important and not mutually correlated. The results of group comparisons are not included in this report. Discharge dynamics are characterized by means of discharge extremity classes O_1 through O_5 for the high discharges, and U_1 through U_5 for the low discharges (see Section 5.5). Both are plotted in a histogram (Figure 6.3). The streams on the left-hand side of the plot are strongly dynamic (RE, SZ); towards the right-hand side the streams become more constant (SN, OB).

Figure 6.3 Duration of discharges (days/year) in discharge extremity classes (see for their definition Section 5.5) , for the nine studied streams.



Substratum

The average percentages of substrate cover for the five main substrate types were determined for each stream. The streams are ordered according to stream type (Figure 6.4). The proportion of each substrate type differs between all streams and no relation to stream type is seen. Important to macro-invertebrates are the dynamics in their habitat, and thus the movement of the substrate. Therefore, the standard deviations of each substrate type per stream was cumulatively plotted (Figure 6.5). The higher the bar, the more change occurred in substrates. Two streams are quite constant (RB, SN), two are intermediate (TB, OB), five are dynamic (BB, SZ, KB, RE, FB) and one stream is very dynamic (RO) in its substrate pattern in time.

Figure 6.4 Average percentages of substrate cover for the five main substrate types.

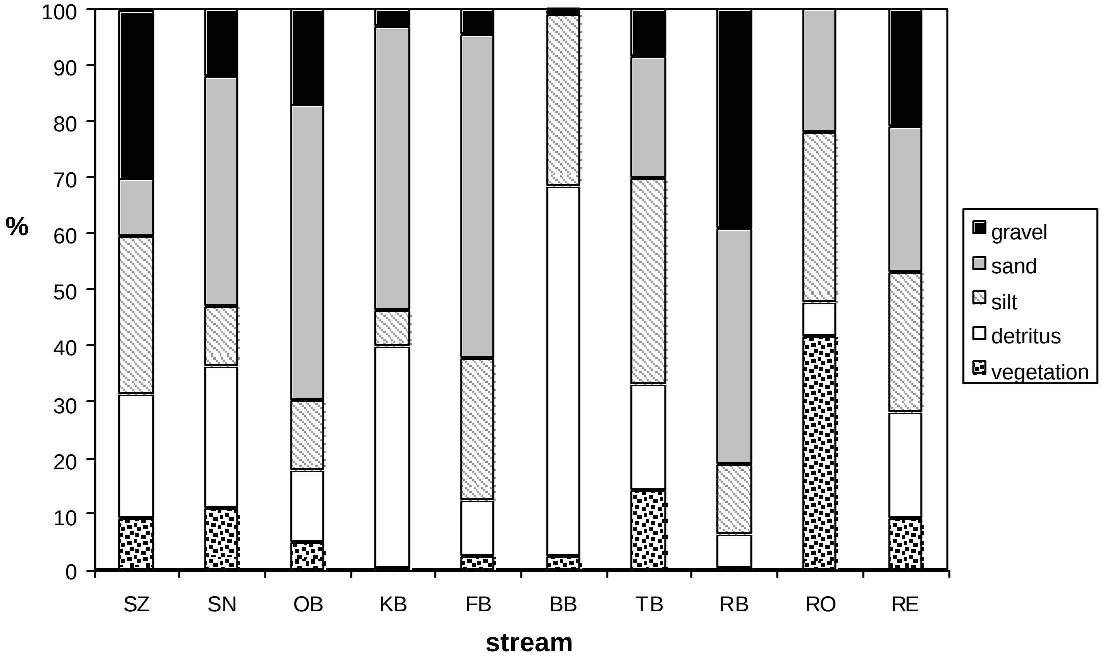
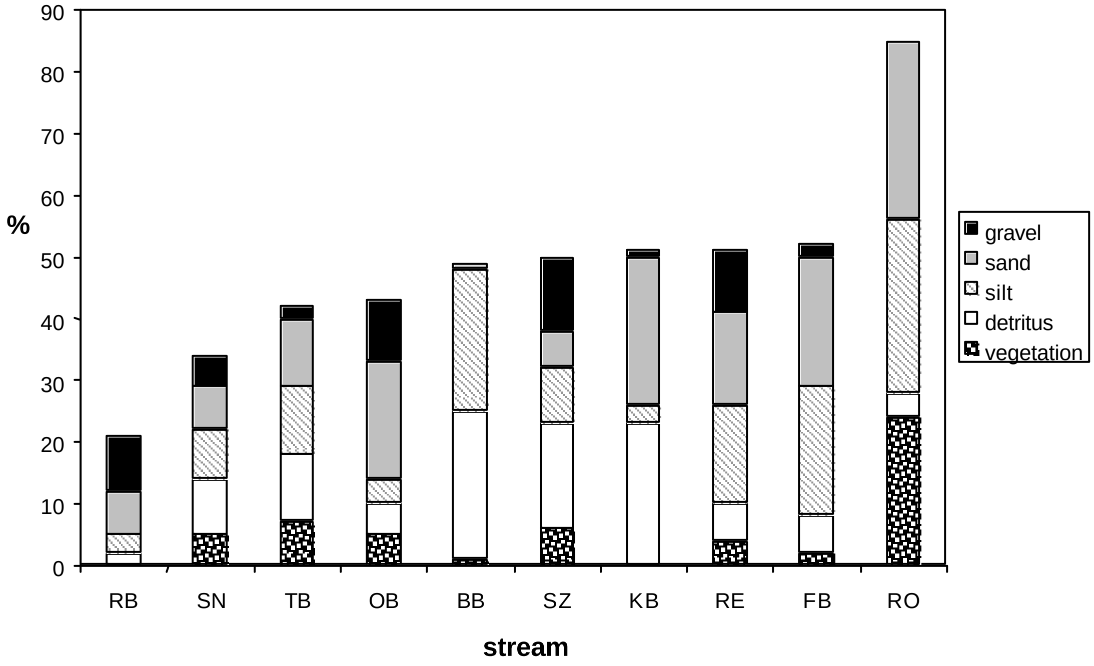


Figure 6.5 Percentage of variation in substrate cover in time.



Hydrology – substratum relationships

To relate hydrology to substratum a procedure was set up to select the best possible regression model in which the hydrological parameters are the predictors and the individual substrates the response parameters. Therefore, the hydrological parameters were grouped taking into account the discharge characteristics, the extreme and normal ranges, and of both the temporal patterns.

The procedure RSELECT (program GENSTAT) was used to select the best test group with the best subset of predictor parameters in the best generalized linear model. Best is defined as having:

- a minimum number of predictors
- the highest goodness of fit checked by its variance ($R^2 > 50\%$), and
- predictors that are significant to a 95 % level ($P > 0.05$)

To test the major hydrological parameters the predictors were divided into two test groups. Test group I refers to stream discharge characteristics and their temporal parameters. Test group II refers to extreme and normal ranges and their temporal parameters.

Table 6.4 Relative chance of prediction for test group I.

Test group I											
discharge parameter	$Q_{av.}$	Q_{10}-Q_{50}	Q_{50}- Q_{70}	$< Q_{10}$	$> Q_{70}$						total
	0.18	0.12	0.12	0.14	0.07						0.13
substrate type	sand	sand-silt	gravel	leaves	fine detritus	coarse detritus	vege-tation	bran-ches	clay	Nuphar	
	0.28	0.33	0.17	0.23	0.40	0.25	0.30	0.60	1.00	0.80	0.32
stream	RE	SN	SZ	TB	OB	KB	RB	BB	RO		
	0.51	0.09	0.30	0.20	0.34	0.20	0.00	0.95	0.33		0.32
discharge period (days)	1	7	14	21	28						
	0.24	0.33	0.29	0.35	0.35						0.31

Table 6.5 Relative chance of prediction for test group II.

Test group II											
discharge parameter	U5	U4	U3	U2	U1	O1	O2	O3	O4	O5	
	0.02	0.01	0.03	0.03	0.01	0.02	0.02	0.01	0.01	0.00	0.02
substrate type	sand	sand-silt	gravel	leaves	fine detritus	coarse detritus	vege-tation	bran-ches	clay	Nuphar	
	0.30	0.35	0.27	0.40	0.45	0.18	0.30	0.70	1.00	0.80	0.32
stream	RE	SN	SZ	TB	OB	KB	RB	BB	RO		
	0.69	0.34	0.53	0.03	0.34	0.20	0.00	0.65	0.30		0.34
discharge period (days)	1	7	14	21	28						
	0.15	0.33	0.44	0.40	0.45						0.35

Taking the criterium that the probability should at least be greater than 0.5 for both test group I and II it is concluded that only the substrates which are always present in about the same cover percentages are well predicted (branches, clay and Nuphar). Furthermore, the Forest stream (BB) and the Reusel (RE) are predicted in both groups while in group II also Springendal stream South (SZ) joins. The prediction of the Forest stream is a consequence of its constant discharge with a seasonal character and its dominant organic substrate layer also seasonally established. The Reusel and Springendal stream South are predicted because of their more flashy regimes, which during low flows show strong increases in silt cover.

It can be concluded that substrate patterns are difficult to predict in near-natural streams. A careful conclusion could be that a more flashy stream would be better predicted by discharge dynamics (extreme and normal ranges) parameters. A combination of several arguments explain the absence of a relation:

- major substrate changes are due to seasonal events of litter fall (autumn) and leaf decomposition

- discharge extremes occur quite unpredictable and rarely (with a recurrence interval of one year or longer)
- unpredictable natural processes like dam formation, sand-bar movement and erosion-deposition change substrate patterns without clear and direct hydrological causes, and
- human interference like maintenance of streams disturb the substrates independently

These arguments do support the hypothesis that lowland streams compose an unpredictable environment for macro-invertebrates.

Macro-invertebrates

In total 249 macro-invertebrate taxa were collected in the 162 habitat samples. All taxa were identified, most of them down to species level. All data collected during 1997 and 1998 were ordinated to describe the variations in taxon distribution and abundances. The major ordination parameters are listed in Table 6.6. The DCCA-ordination (Figure 6.6) shows the relationships between macro-invertebrates and habitat variables. The variables significantly explain the macro-invertebrate distribution (P=0.05; unrestricted permutation test). The individual streams were used as an explaining environmental variable. Six out of ten streams occurred to be important explanatory variables in the analysis. Furthermore, several habitat variables are important. Both habitat variables and streams are not completely independent. Several habitats are more or less dominant in only one or a few streams.

A second DCCA-ordination (not shown) was done by leaving streams out as explaining variables. Then there was a slight drop of the eigenvalue, indicating the importance of streams as explanatory variable. The species-environment correlation drops from 92 to 75 %. Streams are thus important in the distribution of the macro-invertebrates. But the resulting diagram also shows that the macro-invertebrate distribution pattern remains the same over the habitat variables. This confirms a strong relationship between streams and certain habitats.

Table 6.6 Ordination (DCCA) characteristics of the habitat - macro-invertebrate analysis.

Ordination characteristics	**axis 1**	**axis 2**	**axis 3**	**axis 4**	**Over-all parameters**
Eigenvalue	0.40	0.25	0.17	0.14	
Taxa – environment correlation	0.98	0.96	0.96	0.91	
Cumulative % variance in taxa	7.8	12.6	15.9	18.6	sum ‘unconstrained’ 5.2
Cumulative % variance in taxon-environ.	12.0	19.5	24.5	28.7	sum ‘canonical’ 3.4
Significance axis 1: eigen value	0.40				
F-ratio	5.50				2.10
P value	0.01				0.01

Figure 6.6 DCCA ordination diagram for axes 1 and 2. Only environmental variables with an interset correlation > 0.4 are shown (arrows). Letters in grey refer to macro-invertebrate habitat types (OM = organic material); bold letters refer to streams

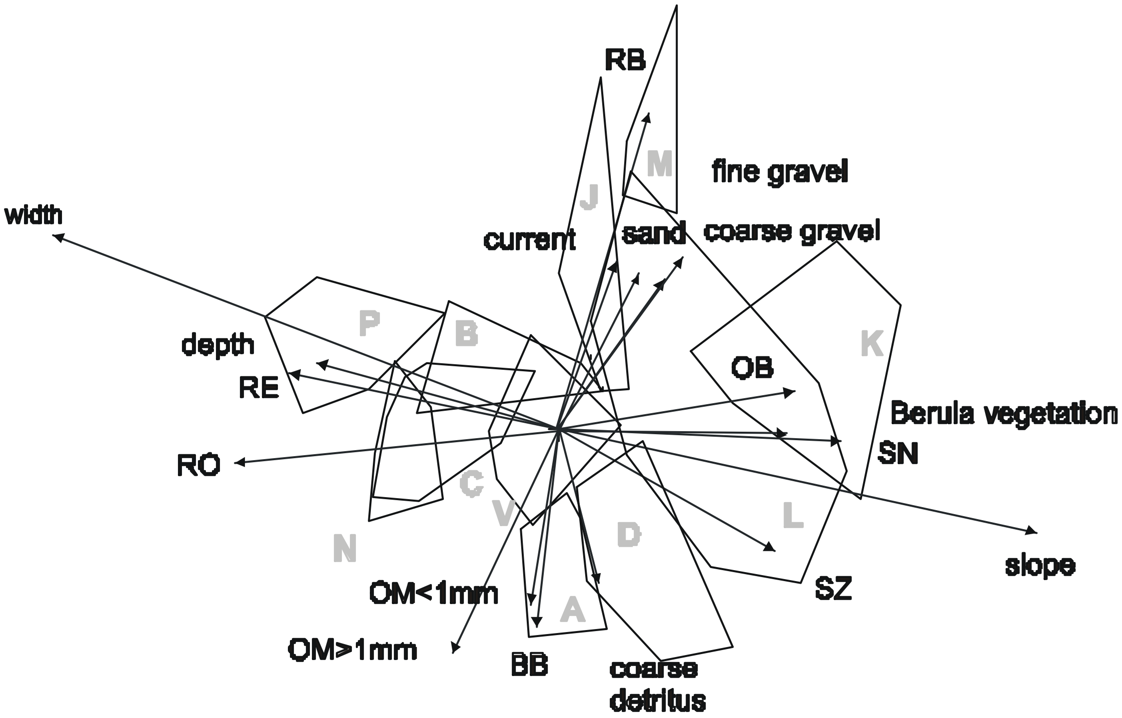
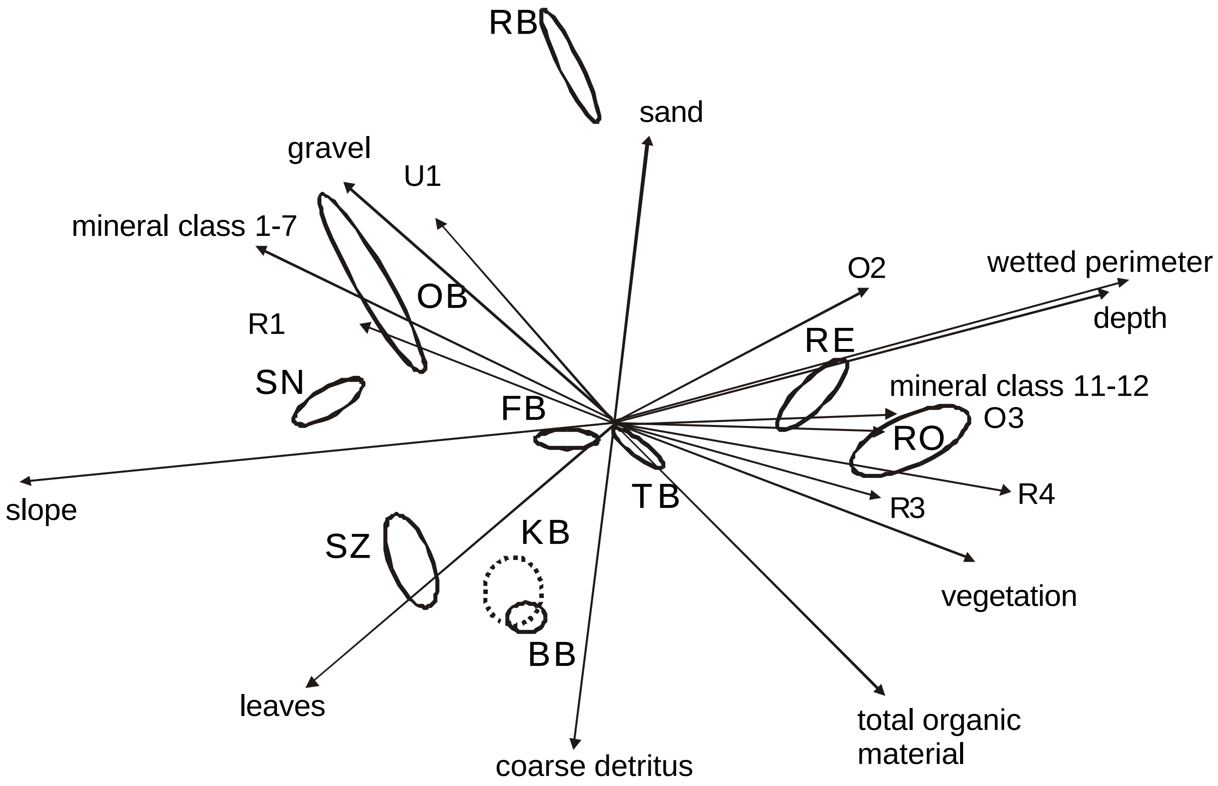


Table 6.7 Ordination (DCCA) characteristics of the stream – macro-invertebrate analysis.

Ordination characteristics	**axis 1**	**axis 2**	**axis 3**	**axis 4**	**Over-all parameters**
Eigenvalue	0.45	0.28	0.18	0.12	
Taxa – environment correlation	1.00	1.00	1.00	1.00	
Cumulative % variance in taxa	18.9	30.5	38.2	43.3	sum ‘unconstrained’ 2.39
Cumulative % variance in taxon-environ.	19.0	30.4	38.2	43.5	sum ‘canonical’ 2.39
Significance axis 1: eigen value	0.45				
F-ratio	5.50				2.10
P value	0.01				0.01

Figure 6.7 DCCA ordination diagram for axes 1 and 2. Only environmental variables with an interset correlation > 0.4 are shown (arrows). Letters refer to streams (ellipses).



Therefore, another ordination was performed (Figure 6.7) at the level of the whole stream by combining all habitat samples per stream into one sample per season. In this run hydrology parameters were included too. The ordination characteristics are given in Table 6.7. Besides substratum variables also hydrology explains the macro-invertebrate distribution. Macro-invertebrates respond to variables that together compose individual streams. The ordination diagram shows a strong gradient along the first axis that is explained by the high and low discharge extremity classes on the right (R_3, R_4) versus the normal range (R_1) on the left. Discharge dynamics do somehow relate to slope and dimensions of the streams. Along the second axes the substrates explain the remaining differences between streams.

From both the habitat and the stream analysis it becomes clear that both substrates and hydrology explain the macro-invertebrate composition in the studied streams. The sum of all constrained eigenvalues using all explanatory hydrological and substrate variables and no covariables was 2.391. The total amount of variance (inertia) in the species data was also 2.391, and thus all variance in species data (100%) is explained by the explanatory variables.

Table 6.8 Proportion of variance explained by environmental variables for groups of hydrological, substrates and stream variables.

Parameter groups (number)	Variance (%)	Discharge dynamics parameters per number of days	Variance (%)
short term discharge characteristics (15)	70	1	35
long term discharge characteristics (12)	82	3	44
discharge dynamics (16)	92	7	49
stream discharge characteristics (14)	84	14	74
substrates (17)	100	21	68
stream characteristics (9)	65	28	76
streams (10)	75	35	75
		70	92
		140	85

The different groups of hydrological, substrate and stream variables were explored (Table 6.8). The substrates explain the macro-invertebrate distribution best (variance 100%), though notice that this group also includes the highest number of parameters. The number of parameters can influence the percentage of variance explained, because each variable will add some explanation (even that based on coincidence) to the total. Still, it can be concluded that a second best explaining variable group is discharge dynamics. Looking over different time periods, it becomes clear that events in the period up to 70 days before sampling took place best explain the invertebrate distribution.

Substrates differed between streams and though we cannot yet explain fully their occurrence and variability in space and time, they strongly influence the macro-invertebrate distribution. Therefore, the relation between macro-invertebrates and substratum expressed in the mineral material parameter 'grain size fraction' and the organic material parameter 'organic matter content', is calculated. The mineral material was classified in the following manner, with the grain size between brackets:

- coarse sand (> 0.50 mm)
- intermediate sand (0.25 - 0.50 mm)
- fine sand (0.125 and 0.25 mm)
- very fine sand (0.063 - 0.125 mm)
- silt (< 0.063 mm)

The organic material was classified in the following manner, with the organic matter content indicated between brackets:

- very high organic matter content (> 10 %)
- high organic matter content (4 - 10 %)
- medium organic matter content (1 - 4 %)
- low organic matter content (< 1 %)
- leaves
- vegetation

All mineral and organic material classes and also the field observed substrates were tested by a chi-square test combined with an IR-score (Table 6.9). The same was done for stream velocity classes (Table 6.10).

Table 6.9 Number of indicative taxa per substratum class.

Field observed substrates	gravel	sand	fine detritus	coarse detritus	leaves	plants
Number of indicative taxa	14	7	22	50	38	71
Grain size fractions	gravel	coarse sand	intermediate sand	fine sand	very fine sand	silt and lutum
Number of indicative taxa	21	14	11	44	27	32
Organic matter content	low	mediair	high	very high	leaves	plants
Number of indicative taxa	13	37	27	51	32	38

Table 6.10 Number of indicative taxa per stream velocity class.

Stream velocity class (cm/s)	0-2.5	2.5-5	5-7.5	7.5-10	10-15	15-20	20-25	> 25
Number of indicative taxa	11	36	33	17	27	12	8	7

The number of taxa indicating a specific substrate, either a grain size fraction, the organic matter content or the field observed substrate type, is high to very high. This supports the ordination results. More in detail taxa are more indicative for certain grain sizes and/or organic matter classes than the observed mineral or organic matter types observed in the field. On the other hand the leaves and plants show more indicative taxa observed in the field. The number of indicative taxa for a stream velocity range are about equally distributed, only the highest classes have less.

6.5 Discussion

Hydro-morphology

Looking at the results of discharges and discharge regimes it can be concluded that all nine streams are classified by both parameters into the same classes. These three discharge classes are given in the columns of Table 6.11. Furthermore, substrate patterns differ between all streams and show more or less dynamic patterns. The streams are also classified according to substrate dynamics classes (rows in Table 6.11). By combining both, Table 6.11 shows the discharge–substratum relationships that are here called the hydro-morphological character.

Table 6.11 Hydro-morphological characterisation of nine studied streams.

Substrate classes	Discharge classes		
	constant	intermediate	flashy
constant	SN	RB	
intermediate	OB	TB	
dynamic		BB, KB	SZ, RE
very dynamic			RO

Discharge–substratum combinations appear not to show simple linear relationships. As expected, flashy streams with a constant substrate pattern do not occur, and neither are there any constantly discharging streams with a dynamic substrate pattern. Streams can have a more constant discharge in time and still show intermediate substrate dynamics, as is shown by the stream (RB) with an intermediate discharge and a constant substrate pattern. This is due to a number of stable gravel banks within the streambed. Also dominated by gravel and thus more stable is the streambed of the 'Springendal stream South' (SZ), despite the flashy discharge dynamics.

Macro-invertebrate distribution

Despite the fact that the macro-invertebrate-habitat ordination without stream parameters versus the one with stream parameters showed a slight decrease in eigenvalues, and their species-environment correlations, and the explanatory variables remained almost the same. The six out of ten stream explaining streams in the first ordination can thus be left out without a major change in the diagram. Only gravel was replaced by median grain size, though both parameters describe roughly the same habitat feature. The macro-invertebrate distribution is related to habitat and these habitats seem to be strongly represented in often only one or two of the studied streams.

The ordination on the scale of streams included also a number of hydrological variables. The major ordination pattern is comparable to the habitat ordination, with about the same explanatory habitat variables combined with some of the discharge dynamics ones. The stream level ordination showed a gradient from flashy streams (R_3 and R_4) towards constantly discharging streams (R_1) according to the series: RO, RE, TB, group of BB, FB, KB; RB, SZ, and group of OB, and SN. This gradient does not fully correspond to Table 6.10 because of the effect of substrate and other environmental conditions affecting the ordination diagram. Note the apparently the specific position of SZ in relation to OB and SN.

In general, most indicative macro-invertebrates prefer specific habitats. These habitats occur under specific conditions which, within these ten streams, occur in one or a few streams, which in their turn are related to individual discharge regimes. More data on different streams with different and comparable hydrological regimes are necessary to decide on a discharge-related preference for macro-invertebrates.

7 TERRESTRIAL ECOLOGY OF LOWLAND STREAMS

J. Runhaar & P.C. Jansen

7.1 Introduction

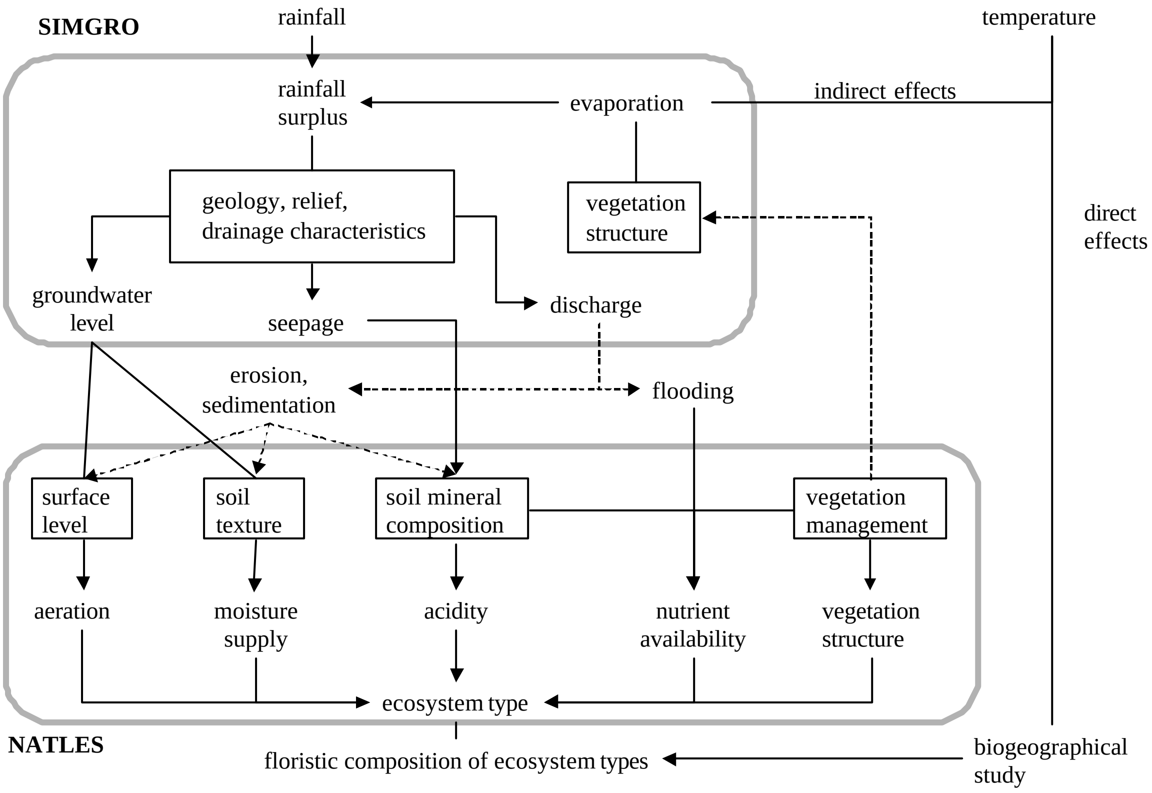
In this study a distinction is made between indirect and direct effects of climatic changes. The *indirect effects* are a result of changes in hydrology, and do not only depend upon climatic conditions such as rainfall and evaporation, but also on characteristics of the area such as soil texture, relief and drainage. The main indirect effects distinguished in this study are (see Figure 7.1):

- changes in aeration and moisture supply due to changes in watertable and evaporation
- changes in base regulation and acidity due to changes in upward seepage intensity
- changes in nutrient status and dynamics due to changes in flooding frequency and sedimentation

Changes in floristic composition as a result of increased temperature are seen as *direct effects*, because they are independent of the abiotic characteristics of the area. These effects are described in Section 10.2.

To determine the indirect effects we made use of the model NATLES (NATure oriented Land-Evaluation System), that has been developed to evaluate the effects of hydrological measures and changes in land use on the distribution of ecosystem types and associated vegetation types (Runhaar et al. 1999). In this model ecosystems are classified in terms of vegetation structure and abiotic site factors such as aeration, moisture supply, acidity and nutrient supply, using a limited number of classes per site factor.

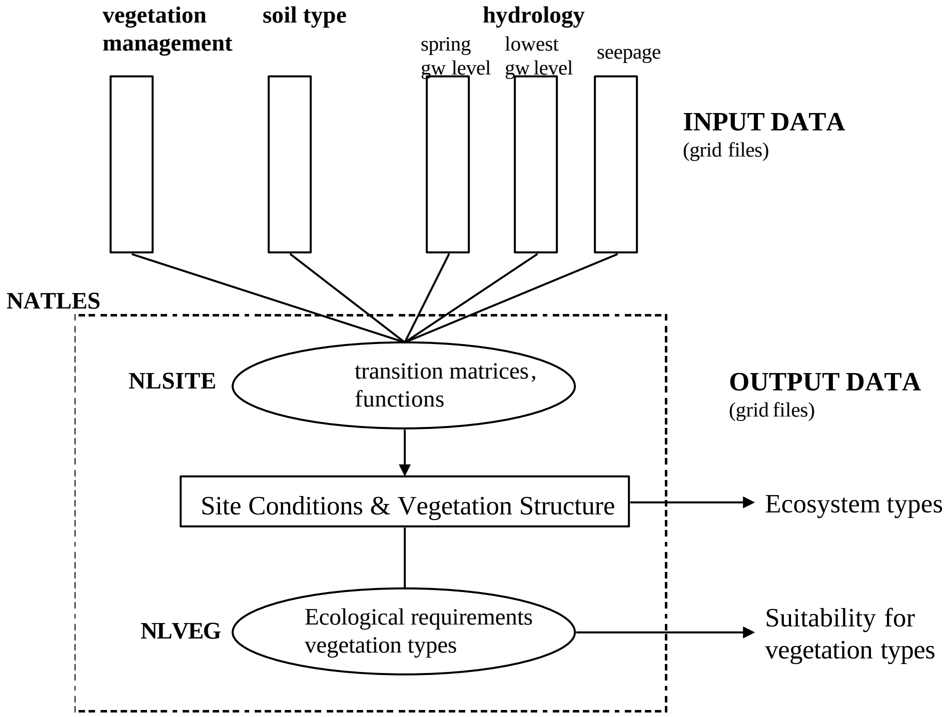
Figure 7.1 Direct and indirect effects of climate. Indirect effects depend upon characteristics of the area such as geology and soil texture. To predict these effects the models SIMGRO and NATLES are used. Direct effects, mainly effects of changes in temperature, are independent of area characteristics. Dotted lines represent relationships not modelled in this study.



7.2 Calculation of effects with the NATLES model

The NATLES model used in this study is a model meant for use in land-evaluation studies and in hydro-ecological modelling. It can be used to determine the suitability of sites for the maintenance or development of certain ecosystem types and associated vegetations. It is an ArcView application written in the AVENUE language (ESRI 1996). The input consists of ArcView grid files with geographical data on soil type, hydrology and vegetation management. The output consists of maps with the distribution of predicted ecosystem types, and the suitability for the development of certain vegetation types (Figure 7.2).

Figure 7.2 Conceptual framework of the Natles model.



The ecosystem types are defined in terms of vegetation structure and abiotic site conditions. The site conditions are predicted as a function of soil type, management and hydrology, using transition matrices that have been compiled on the basis of simulation experiments with models such as SWAP (Van Dam *et al.* 1997) en SMART (Kros *et al.* 1995), empirical data and expert judgement. Predictions are made for situations where vegetation and site conditions are more or less in equilibrium with hydrology and management, which is assumed to be the case after a period of approximately 10-30 years.

The detail of the produced maps depends upon the detail of the input data, but in general the model is meant for use in studies on a 1:10.000 to 1:50.000 scale. In this study grid cells with a size of 25 x 25 m were used. The NATLES version used in this study (1.2) is similar to the version 1.1 described by Runhaar *et al.* (1999), but for the prediction of the effects of climatic change the moisture regime classification has been modified (see next section).

The site factors that are considered most relevant for vegetation development are chosen to serve as ecosystem classification characteristics. They are moisture regime, acidity and nutrient availability. Salinity is equally important, but has not yet been incorporated in the model and is less relevant for inland situations where fresh water prevails. To characterize the ecosystems the site factors have been classified into discrete classes. The site factor classification is basically the same as in the classification of ecotopes by Stevers *et al*. (1987) and Runhaar *et al*. (1987, 1994, and 1999) but some classes have been added to increase the detail. In the following a short description will be given of the classification of site factors and it will be indicated how the classes are predicted as a function of soil type, hydrology and management.

7.2.1 Moisture regime

The term 'moisture regime' is used to indicate a complex of factors that are all in some way linked to the amount of water available. It is used to describe differences in medium (aquatic versus terrestrial systems), aeration and moisture supply (Table 7.1).

Table 7.1 Classification according to moisture regime.

MSW (cm b.s.s.)	MLW (cm b.s.s.)	Potential moisture stress (d)	Description of the classes
< -50	-	-	Permanent deep water
-50 – -20	< 0	-	Permanent shallow water
-50 – -20	= 0	-	Non-permanent shallow water
-20 – 0	-	-	Very wet
0 – 25	-	-	Wet
25 – 40	-	-	Very moist
> 40	-	<14	Moist
> 40	-	14-30	Moderately dry
> 40	-	>30	Dry

MSW: Mean Spring Watertable *MLW*: Mean Lowest Watertable
Potential moisture stress: average number of days the soil moisture potential is less than -12.000 cm at a depth of 12.5 cm, assuming a standard grass layer

As shown by Runhaar *et al.* (1996) the relative abundance of hygrophytes[1] is most directly related to the watertable in spring, probably because the aeration in spring – when most species sprout or germinate – is most critical for the competition of hygophytes and non-hygrophytes. The boundary between sites dominated by hygrophytes and sites dominated by

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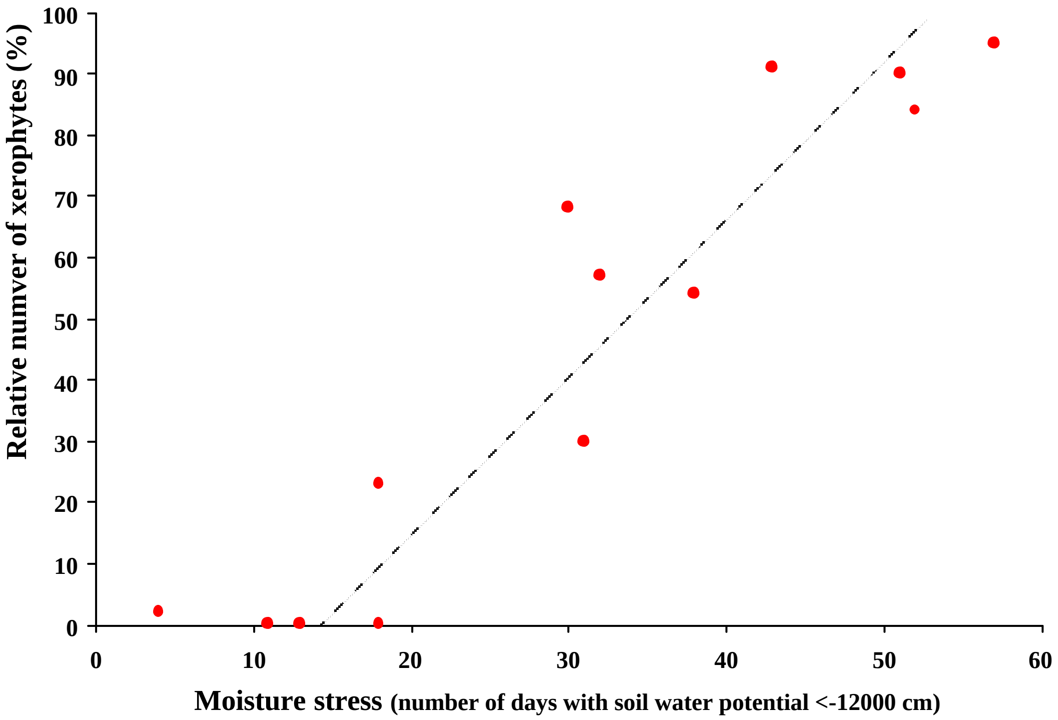
[1] For definition of hygrophytes, mesophytes and xerophytes see table 7.2

Table 7.2 Comparison of the grouping of species as to moisture regime by different authors. Unless otherwise stated in this study the classification according to Runhaar *et al*. 1987 is followed.

	Classification according to moisture regime		
Author	Hygrophytes	Mesophytes	Xerophytes
Runhaar et al. 1987	Species characteristic for wet sites	Species characteristic for moist sites	Species characteristic for dry sites
Klapp (1965)	7-10	4-6	1-3
Ellenberg (1992)	7-9	4-6	1-4
Londo (1988)	Obligate phreatophytes (W,F)	Facultative phreatophytes (V, K, P, D)	-
Iversen (1936)	Polyhygroob	Oligohygroob	Xeroob
Schimper (1909)	Hygrophyte	Mesophyte	Xerophyte
Reed (1988)	Obligate wetland	Facultative	Upland

Figure 7.3 Relation between relative number of xerophytes in the vegetation and moisture stress. Source: Jansen *et al*. 2000.



mesophytes and xerophytes coincides with a Mean Spring Watertable (MSW; defined as average watertable in March-April) of about 25 cm below soil surface. Therefore this level has been used as the boundary between the classes ‘wet’ and ‘very moist’. The difference between moist and dry sites is based on the moisture supply of the soil, with dry sites defined as sites with large moisture deficits during the growing season, dominated by obligate xerophytes[1]. Jansen *et al*. (2000) found that the potential moisture stress[2] is a good predictor for the number of xerophytes found in grassland vegetations (Figure 7.3). At a potential moisture stress of more than 30 days obligate xerophytes dominate the vegetation, whereas at a moisture stress of less than 14 they are absent. Although the number of observations in this research was rather small (n=17), the relation found is the rather clear (R=0.9). Since other data on this relationship are scarce, the data of Jansen *et al*. were used to define the classes moist, moderately dry and dry.

In this classification it is implicitly assumed that moisture stress will only occur on sites with low watertables (MSW more than 40 cm below soil surface). In the present climatic conditions, with moderate summer temperatures and rainfall equally distributed over the year, this assumption is valid for most situations. However, with changing climatic conditions situations might come to exist with high watertables and aeration problems in winter, and moisture stress in summer. Therefore the classes ‘very wet’, ‘wet’, and ‘very moist’ have been subdivided on the basis of moisture stress (Table 7.3). Especially in situations with more extreme climatic conditions it is assumed that sites with multiple stress (both anaerobic conditions and moisture stress) will increase.

The potential moisture stress depends upon the soil type, watertable and precipitation excess. In the study of Jansen *et al*. (2000) calculations were made with the model SWAP (Belmans et al. 1983, Van Dam *et al*. 1997, Van Dam 2000). However, because of the large number of grid cells for which calculations have to be made it is impossible to use this model for every single grid cell. Instead SWAP was used to derive functions that predict the moisture stress as a function of soil type, precipitation excess and the number of consecutive days that the groundwater is below a critical level for sufficient moisture supply to the rooting zone. Section 5.4 describes in more detail how the moisture stress was calculated with the SIMGRO hydrological model and the functions derived from SWAP.

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[2] calculated as the number of consecutive days the soil moisture potential is less than -12.000 cm at a depth of

Table 7.3 Subdivision of the classes ‘very wet’, ‘wet’, and ‘very moist’ on the basis of moisture stress.

Subclass	Code	Moisture Stress (days)
No moisture stress	-	< 3
Little moisture stress	*	3-13
Moderate moisture stress	**	14-30
Large moisture stress	***	> 30

7.2.2 Acidity

Table 7.4 shows the acidity classes used in the NATLES model. The acidity is predicted on the basis of soil type, management and hydrology. In the study area only non-calcareous soils occur, which means that except for agricultural areas, where lime is applied, the soils are predominantly acid. In the river valleys younger and more mineral-rich soils occur with a relatively high base-saturation, which are only moderately acidic. In the nature areas weakly acidic to neutral conditions can be found in upward seepage areas, where carbonate in the groundwater forms a buffer against acidification. Flooding with carbonate-rich river water forms an additional buffering mechanism, but has not been taken into account in the NATLES calculations because of the lack of sufficient data to predict the effects.

In non-seepage area the acidity of the soil in non-limed conditions was estimated on the basis of average carbonate-content and base-saturation of the soil. To calculate the acidity in upward seepage areas use has been made of the soil acidification model SMART (Kros *et al.* 1995). As with the prediction of moisture stress, dose-effect functions calculated with SMART were used instead of the model itself. These functions give the pH as a function of upward seepage intensity, spring watertable, soil type and groundwater composition. In the SMART model five soil types are distinguished, of which two types commonly occur in the study area: ‘poor sands’ and ‘rich sands’ (see Kros *et al.* 1995 for soil classification used). The upward seepage intensity is calculated with SIMGRO as the gross amount of upward seepage (in mm/d, averaged over the year) reaching the upper soil layer (20 cm). Section 5.3 describes how these calculations were made. As to groundwater composition distinction is

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12.5 cm, assuming a standard grass layer

Table 7.4 Classification as to acidity. Source: Runhaar *et al*. 1999.

PH-H_2O	Description of the classes
< 4,5	Acidic
4,5-5,5	Moderately acidic
5,5-6,5	Weakly acidic to neutral
> 6,5	Basic

made between soft water (Ca ca 7.5, HCO3 ca 27 mg/l), moderately alkaline water (Ca ca 15, HCO3 ca 55 mg/l) and alkaline water (Ca ca 40, HCO3 ca 146 mg/l). The groundwater composition has been derived from the study by Van Ek *et al*. (1998), in which the type of groundwater in upward seepage areas has been estimated on the basis of available chemical data and geohydrological information.

7.2.3 Nutrient availability

As there are hardly any quantitative data on the relationship between nutrient availability (N,P and K) and vegetation composition, and because of the lack of knowledge on the precise relationship between nutrient supplies, nutrient availability and productivity, the classification as to nutrient availability is by necessity of a qualitative nature. Because of the scarce information only three classes have been distinguished: poor, moderately rich and rich. These classes are primarily defined on the basis of species occurring on the sites, defining ‘poor’ sites as sites dominated by species classified as indicative for poor conditions and ‘rich’ sites as sites dominated by species classified as indicative for rich conditions. The classification of species is according to Runhaar *et al*. 1987 (Table 7.5).

For grassland vegetations the sites can be described more quantitatively in terms of productivity and mineralization. Table 7.7 gives a description of the classes according to

Table 7.5 Comparison with the classification of species as to nutrient availability by Runhaar *et al*. with the classifications by Clausman *et al*. (1987), Ellenberg *et al*. (1992) and Klapp (1965).

	species indicative for poor sites	species indicative for moderately rich sites	species indicative for rich sites
Ellenberg N	1-3	4-7	7-9
Klapp N	1-3	2-4	4-5
Nutrient indication Clausman	0-40	40-60	60-100

Blokland and Kleijberg (1997). However, these data are of a tentative nature. Productivity, for example, is not only limited by nutrient availability but also by management, amount of solar radiation and moisture supply and therefore can only be used as an indicator for nutrient availability within a certain range of climate and management conditions. In dry grasslands, where soil moisture supply is a limiting factor, productivity may be less than indicated in Table 7.6. The amount of nitrogen or phosphorous present is only representative for the nutrient availability in situations where these elements are limiting the productivity. As shown by Runhaar (1989) and Boeker (1954) there is only a very weak relationship between amounts of available N and P and the species composition and productivity of sites.

Table 7.6 Characterization of nutrient-availability classes according to Blokland and Kleijberg (1997).

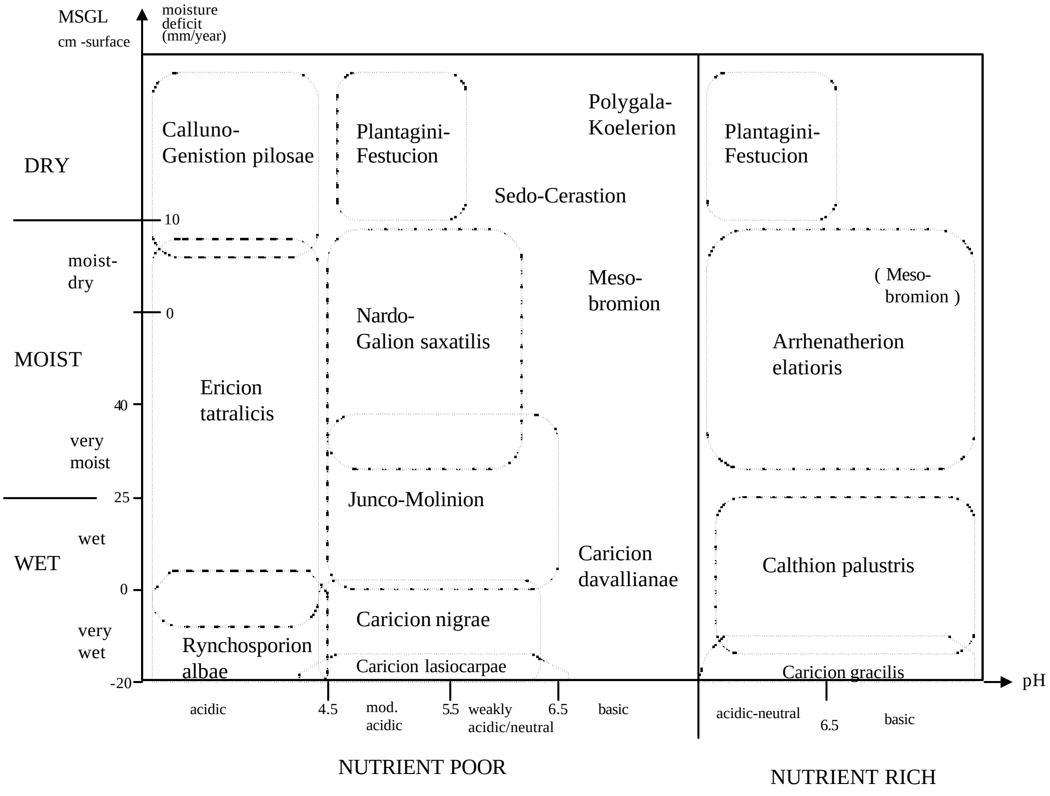
	In groundwater and surface water		In soil				
	NO3 (mg/l)	PO4 (mg P/l)	C/N	C/P	N-min	Ellenberg N	Productivity (dry yield in kg/ha x 1000)
Nutrient poor	< 1	< 0.04	> 35	> 750	< 60	1-4	< 4
Mod. nutrient rich	1-2	0.04-0.10	20-35	300-700	60-180	5-6	4-8
Nutrient richt	2-3	>0.10	<20	<300	> 180	7-9	>8

In the NATLES model the nutrient availability status is predicted as a function of vegetation management (fertilized versus non fertilized sites) and mineralization of organic matter. Because of the lack of a precise quantitative definition of the nutrient availability classes no attempts have been made to predict the classes on the basis of mechanistic models. Instead estimates have been made of the nutrient availability status per combination of management type, soil type (amount and type of organic matter), pH (predicted on the basis of soil type, management and hydrology; see previous section) and groundwater (Mean Lowest Watertable predicted with SIMGRO). Nutrient rich sites are predicted for fertilized agricultural land only, whereas moderately nutrient rich sites are predicted mainly on sites rich in organic matter and a high pH. In other situations mainly nutrient-poor conditions are predicted. In the model fertilization with flooding nutrient-rich river water has not been taken into account. In Section 10.2 the implications of this omission will be discussed.

7.3 Relevant ecosystem types and associated vegetations

In this study attention is focused on those ecosystem types that are most characteristic for small river systems: species-rich mesotrophic wet grasslands with vegetations belonging to the alliances *Junco-Molinion*, *Caricion nigrae* and *Calthion palustris*. Figure 7.4 gives an overview of the ecological position of these alliances in terms of site conditions, using the classification to site conditions used in the NATLES model (Section 7.2). In this scheme they are represented with other alliances that are characteristic for Pleistocene sandy regions. Only alliances comprising grassland and heathland vegetations are shown: woody vegetations, tall herb vegetations and pioneer vegetations are not represented.

Figure 7.4 Ecological position of Junco-Molinion, Calthion palustris and Plantagini-Festucion vegetations in comparison with other alliances. Nomenclature according to Schaminée *et al.* 1995b, 1996.



7.3.1 Junco-Molinion

Wet grasslands of the alliance *Junco-Molinion* grow on wet and moist soils with a low availability of nutrients. They are found in areas influenced by Ca-rich groundwater, as well as by surface water from a local origin and rainwater. They tolerate only a limited flooding with nutrient-rich surface water, and therefore are often limited to the edges of the brook valleys. The groundwater is relatively acid: a pH of 4.7-5.6 is commonly found for *Junco-Molinion* grasslands in the Netherlands (Jalink & Jansen 1996). The proportion of the different water types that influence the vegetation has an impact on the species composition (Grootjans 1985; Everts & De Vries 1991; Jalink & Jansen 1995). During winter, these grasslands are very wet. The watertable is above or just below surface level for several months. From spring onwards, the watertable falls below surface level. Due to seepage, the watertable does not fall lower than 50-60 cm beneath soil surface for most of the summer period. Ellenberg (1968) mentions 35 and 5 cm below surface level as the highest watertable for respectively moist and wet *Junco-Molinion*. The lowest watertable is 70 and 55 cm below soil surface for moist and wet *Junco-Molinion*, according to Ellenberg (1968).

Character species of the alliance of *Junco-Molinion* are *Succissa pratensis* and *Juncus conglomeratus*. *Luzula multiflora* and *Valeriana dioica* (character species of the order *Molinietalia*) have their optimum in this alliance. For the Netherlands, one association is distinguished: *the Cirsio dissecti-Molinietum* (Schaminée *et al.* 1996). Character species are *Cirsium dissectum*, *Carex panicea*, *Carex hostiana*, *Carex pulicaris* and *Cirsium x forsteri*.

Junco-Molinion meadows used to be widespread in river valleys and other low-lying areas. Nowadays only a few have remained (e.g. Grootjans 1985; Bakker 1990; Everts & de Vries 1991, Runhaar *et al.* 1996). Their decline is caused by drainage, resulting in a replacement of groundwater by rainwater and by an increasing mineralization. Only a small decrease in watertable in nature reserves (a decrease in mean groundwater table in spring from 20 to 40 or 50 cm below soil surface) can have a great impact on species composition. Sensitive species are replaced by dominant, less rare species (Van Beusekom et *al.* 1990; Runhaar 1996). As described above, the change in species composition is caused by a changing pH in the top soil as well as a change in base saturation as a result of a higher impact of rain water compared to Ca-rich groundwater and an increasing mineralization. Moreover, the use of fertilizers has increased, changing nutrient poor meadows into nutrient rich ones. Also, the abandoning of meadows has led to litter accumulation and an increase of tall herbs. And finally, much meadows have been lost because of a change in land use. In the Beerze-Reusel area *Junco-Molinion* vegetations have become very rare. Small patches of *Junco-Molinion* vegetetations are still present at the Smalbroeken area.

7.3.2 Calthion palustris

This ecosystem type used to be widespread in NW Europe on wet soils with a relatively good nutrient availability (Grootjans 1985; Ellenberg 1968). It can be found in situations influenced by calcium-rich groundwater. It is found in relatively base rich, meso- to slightly eutrophic situations. Compared with the *Junco-Molinion*, *Calthion palustris* vegetation is found on more nutrient-rich soils, which may be more frequent flooded with surface water. The hydrological regime is comparable to that of the *Junco-Molinion*: very wet in winter and moist in summer.

Character species of the *Calthion*-alliance are *Lycnhis flos-cuculi*, *Rhinanthus angustifolius*, *Dactylorhiza majalis*, *Caltha palustris*, *Lotus unliginosus* and *Carex disticha* (Schaminée et al. 1996). Six associations are distinguished for the Netherlands. Four of them are potentially found in the higher sand region of the Netherlands: the *Crepido-Juncetum acutiflori* (character species: *Scutellaria minor* (weak)), *Ranunculo-Senecionetum aquatici* (character species: *Senecio aquaticus*), *Scirpetum sylvatici* (character species: *Scirpus sylvaticus*) and *Angelico-Cirsietum oleracei* (character species: *Crepis paludosa*, *Cirsium oleraceum* and locally *Polygonum bistorta*).

During the last decades most of the *Calthion* meadows have been transformed into high-productive pastures through drainage and additional use of fertilizers. In the Netherlands, *Calthion* meadows are nowadays only found in nature reserve areas where the use of fertilizers is restricted. In spite of the conservation status of the *Calthion* meadows, many of them are still affected by drainage from adjacent agricultural areas, as is mentioned above for the *Junco-Molinion* grasslands. In the Beerze-Reusel area *Calthion* vegetations are still present at the Smalbroeken, Helsbroek and Westelbeerse Broek areas.

7.3.3 Related vegetations

Because of the lack of free carbonate in the soils that occur in the study area, *Junco-Molinion* and *Calthion* vegetations are restricted to the river valleys where bicarbonate in ground- and surface water and a higher base-saturation form a buffer against acidification. In wet places where infiltration of rainwater prevails, the lack of carbonates in the soil and the percolation with rain water results in acidic conditions. In these sites wet heath vegetations, belonging to the *Ericion tetralicis*, occur (Figure 7.4). Because of the lack of calcareous sediments the pH is normally too low for *Caricion davallianae* vegetations, that prefer more basic conditions. Where conditions are slightly drier and more acidic, *Nardo-Galion* vegetations may occur. They often form a transition zone between the vegetations belonging to the *Junco-Molinion* and the *Ericion tetralicis* alliances. In slightly wetter and more acidic conditions, less species-rich *Carion-nigrae* vegetations occur. In the study area they occur occasionally in nature reserves on places where rainwater stagnates, causing a superficial acidification of the soil.

7.3.4 Ecosystem classification used in presentation of results

The number of ecosystem types distinguished in NATLES is too large to give a good overview of the effects of climate change and changes in water management. For this purpose, a simplified ecosystem classification is used as indicated in Table 7.7. The 'target' ecosystem types in these study are wet and very moist riverine grasslands, that are characteristic for upward seepage areas in the river valleys. For comparison purposes wet and dry heathland ecosystems, characteristic for the infiltration areas, have also been distinguished.

Table 7.7 Simplified ecosystem classification used in presentation of modelling results. Site factor classes as described in Section 7.2. Target ecosystem types indicated in bold.

simplified ecosystem classification used to present result predictions	moisture regime	nutrient avaliability	acidity	associated vegetation types
wet riverine grassland	very wet	poor	mod. acid-basic	Caricion nigrae
		mod.rich		Caricion gracilis
	wet	poor	mod. acid-basic	Junco-Molinion, Caricion davallianae
		mod.rich		Calthion palustris
very moist riverine grassland	very moist	poor	mod. acid-basic	Junco-Molinion, Caricion davallianae
		mod.rich		Calthion palustris
moist riverine grassland	moist	poor	mod.acid-neutral	Nardo-Galion saxatilis
		mod.rich		Arrhenatherion elatioris
wet heath	wet	poor	acid	Ericion tetralicis
very moist heath	very moist	poor	acid	Ericion tetralicis
moist heath	moist	poor	acid	Ericion tetralicis
moderately dry heath	mod. dry	poor	acid	Ericion tetralicis/Calluno genistion
dry heath	dry	poor	acid	Calluno-Genistion pilosae

8 EFFECTS ON REGIONAL HYDROLOGY AND STREAM MORPHOLOGY

P.E.V. van Walsum and J.W.J. van der Gaast

8.1 Introduction

The results of the ‘abiotic’ modelling are for the most part only of interest as intermediate variables that partly determine the outcome of ecological evaluation procedures. But for a good interpretation of the ecological effects it is essential to gain some understanding of the underlying hydrological effects.

8.2 Effects on the soil water and groundwater system

The main water balance terms of the ‘top’ system are presented in Table 8.1. The water balance ‘error’ term ΔB is the amount of water that leaves the region through extractions (37 mm/yr) and through the boundaries (15 mm/yr in the current situation). From the results for the diverse scenarios it becomes clear that the variation of the amount leaving the region is small in absolute terms. Most of the variations of precipitation are directly translated to changes of the discharge, with effects on the evapotranspiration acting as an attenuating term:

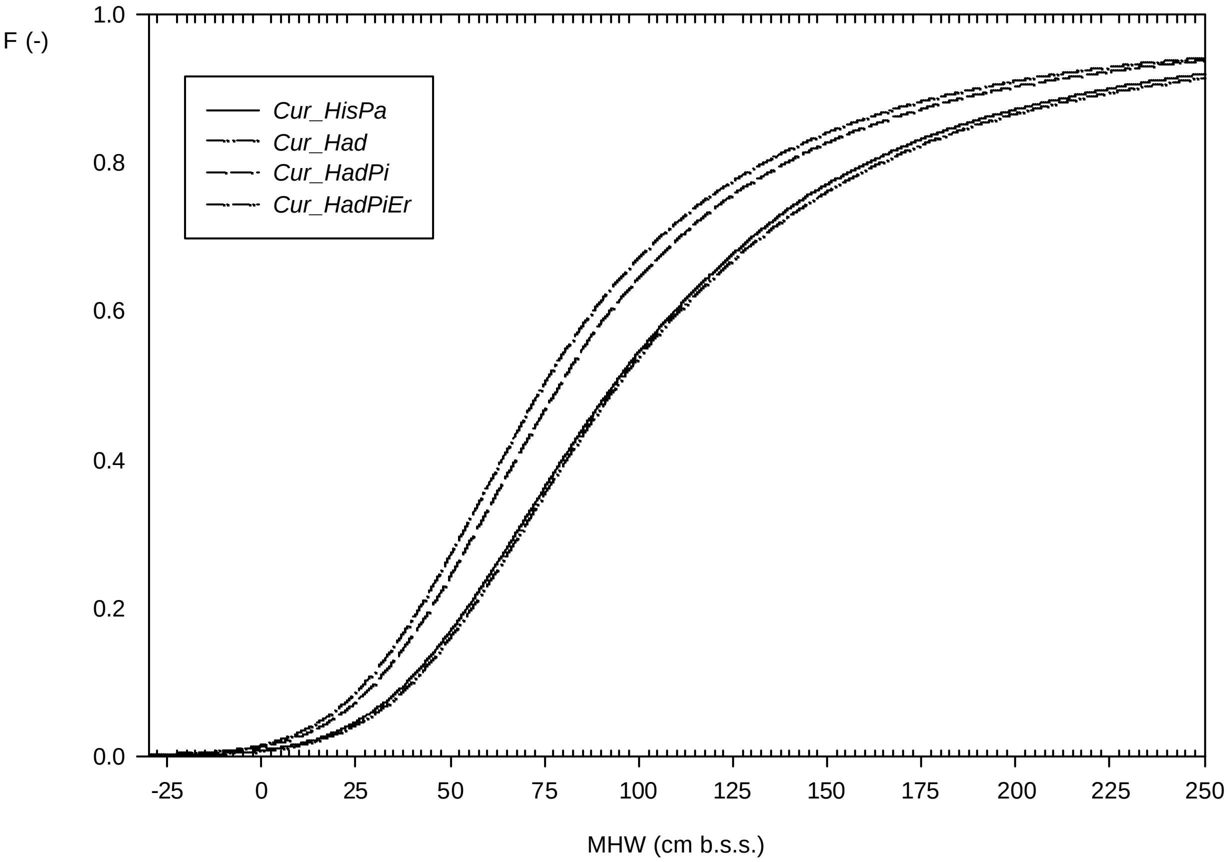
Table 8.1 Water balance terms of scenarios. The balance ΔB is the amount of groundwater water that leaves the regional system through deep extractions and through the boundaries.

Scenario code	P_{winter} (mm/½yr)	P_{summer} (mm/½yr)	P (mm/yr)	E (mm/yr)	Q (mm/yr)	ΔB (mm/yr)
Cur_His	414	381	795	480	263	52
Cur_HisPa	410	380	790	485	250	55
Cur_Had	420	351	771	500	222	49
Cur_HadPi	486	390	876	530	287	59
Cur_HadEr	420	351	771	465	253	53
Cur_HadPiEr	486	390	876	490	324	62
Ehs_His	414	381	795	480	264	51
Ehs_HadPi	486	390	876	529	286	61
EhsBuf_His	414	381	795	476	261	58
EhsBuf_Had	420	351	771	495	220	56
EhsBuf_HadPi	486	390	876	527	285	64
EhsBuf_HadEr	420	351	771	471	242	58
EhsBuf_HadPiEr	486	390	876	498	312	66
EhsBufM_His	414	381	795	477	257	61
EhsBufM_Had	420	351	771	499	214	58
EhsBufM_HadPi	486	390	876	528	283	65

variations of the precipitation are ‘contradicted’ by variations of the evapotranspiration. When comparing the scenarios *EhsBuf_ ..* (with part of the agricutural area turned into a buffer zone) to the rest, it should be realized that not only are the ditches made shallower, but also the sprinkling of the affected agricultural area is turned off. The first factor causes an increase of the evapotranspiration, the second a decrease. In some instances the latter dominates (*EhsBuf_HadPi* has a lower evapotranspiration than *Cur_HadPi*) and in others the former dominates (*EhsBuf_HadPiEr* has a higher evapotranspiration than *Cur_HadPiEr*).

Especially the scenarios with increased precipitation have a large impact on the groundwater regime. In Figure 8.1 this is shown in terms of the cumulative frequency curves of the Mean Highest Watertable as computed for the 25 x 25 m grid used in the downscaling of watertables (Section 5). The increased evapotranspiration of scenario *Cur_Had* only slightly lowers the Mean Highest Watertables (lowest curve in Figure 8.1). As can be seen from the difference between the curves for scenarios *Cur_HadPi* and *Cur_HadPiEr* the possible

Figure 8.1 Cumulative frequency distributions of Mean Highest Watertables (MHW) for pixels of 25 x 25 m, for several climate scenarios



reduction of crop evapotranspiration factors has a substantial impact: apparently the evapotranspiration during the preceding summer influences the Mean Highest Watertables, even though they occur in the following spring.

In Table 8.2 an overview is given of the effects that the scenarios have on the area $A_{0.5}$ where the ecologically critical level of 0.5 mm/d is reached. An example of changes in the latter is given in Figure 8.2. The results are best analysed by comparing scenarios that differ only in terms of precipitation or only in terms of evapotranspiration. That reveals the separate effects.

Figure 8.2 Increase of the gross upward seepage to the rootzone, for scenario *Cur_HadPi* - scenario *Cur_His*, showing changes for areas with a seepage > 0.5 mm/d.

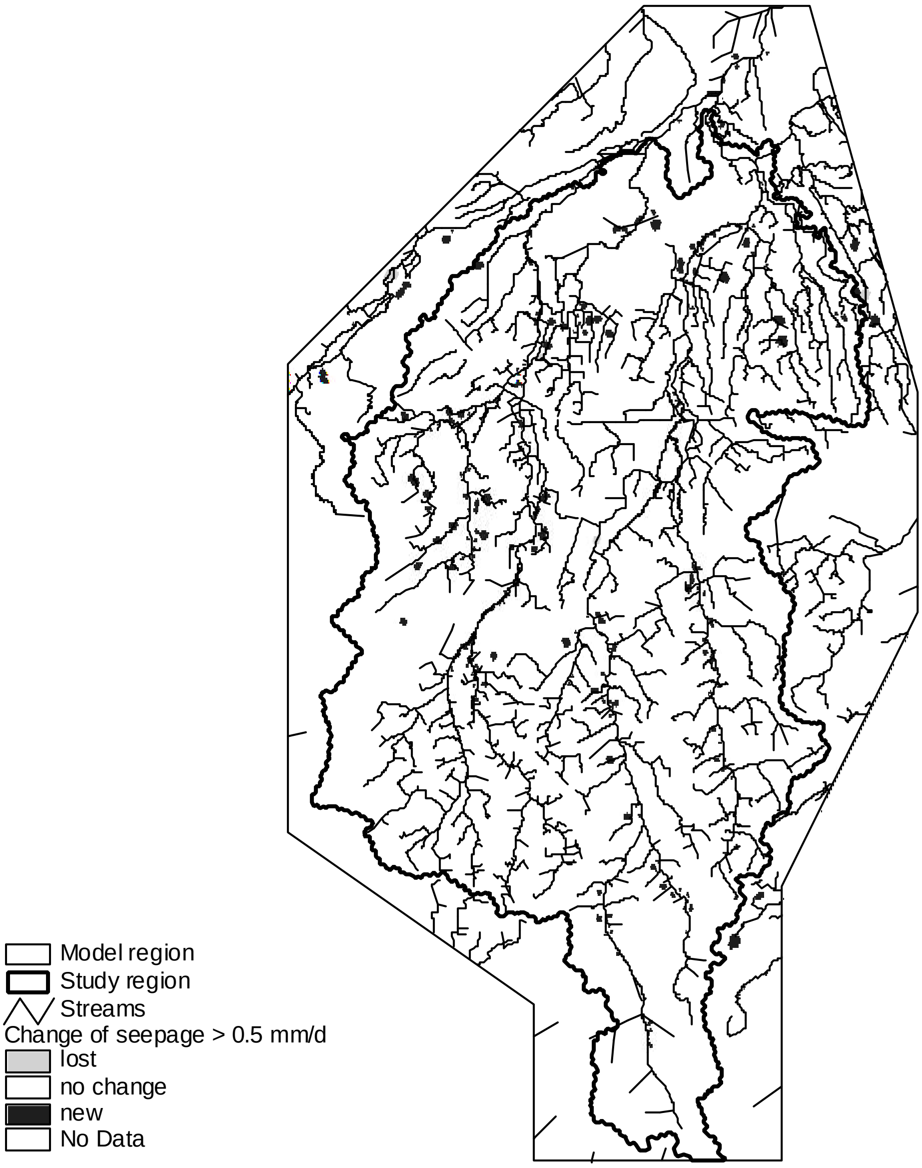


Table 8.2 Simulation results for the gross upward seepage to the root zone. $A_{0.5}$ is the total area with a mean upward seepage to the rootzone exceeding 0.5 mm/d, within the part of the region that is nature area (14 620 ha).

Scenario code	Land and water use, climate scenario (see for a complete description Table 2.7)	$A_{0.5}$ (ha)
Cur_His	Current situation, historic precipitation	798
Cur_HisPa	Current situation, regionally averaged precipitation	763
Cur_Had	Current situation, Hadley downscaled climate data	1073
Cur_HadPi	Current situation, Hadley and KNMI rule-of-thumb	1149
Cur_HadEr	Current situation, Hadley, reduced crop factors	875
Cur_HadPiEr	Current situation, Hadley & KNMI, reduced crop factors	950
Ehs_His	Implemented ecological network Ehs	680
Ehs_HadPi	Implemented ecological network Ehs	980
EhsBuf_His	Ehs and buffer zone of extensive grassland	736
EhsBuf_Had	Ehs and buffer zone of extensive grassland	917
EhsBuf_HadPi	Ehs and buffer zone of extensive grassland	998
EhsBuf_HadEr	Ehs and buffer zone of extensive grassland	878
EhsBuf_HadPiEr	Ehs and buffer zone of extensive grassland	954
EhsBufM_His	Ehs and buffer zone and free meandering main streams	855
EhsBufM_Had	Ehs and buffer zone and free meandering main streams	1030
EhsBufM_HadPi	Ehs and buffer zone and free meandering main streams	1097

Scenario *Cur_HadPi* has a 14% increase of precipitation compared to scenario *Cur_Had*. Increased precipitation raises the watertables in the infiltration areas, and thus increases the upward seepage in the stream valleys. On the other hand increased precipitation also increases the maximum thickness of the precipitation lense in the stream valleys. It then takes longer for the precipitation lense to vanish during the summer period, and thus the gross upward seepage to the root zone becomes less. So the question is which of the two processes has the upper hand. From the results given in Table 8.2 it appears that the influence of the higher watertables in the infiltration areas has the upper hand, but the net effect is not very big: the area $A_{0.5}$ with more than 0.5 mm/d seepage increases from 1073 ha to 1149 ha.

Scenario *Cur_HadEr* has a 7% lower evapotranspiration than *Cur_Had* (Table 8.1). This leads to a large 19%-drop of $A_{0.5}$ from 1073 ha to 875 ha (Table 8.2). This reduction is due to less 'evaporative pull' by the vegetation in the stream valleys, which affects the capillary rise term in Equation 5.2. This evapotranspiration-effect also explains the large increase of $A_{0.5}$ from 798 ha in *Cur_His* to 1073 ha in *Cur_Had*. But if the reduction of crop factors as assumed in the *Er*-scenarios really takes place, the positive seepage effects of climate change are nearly neutralized.

With respect to the land and water use scenarios the most interesting question is what the effects are on the gross seepage to the root zone, as compared to the climatological effects. It appears that in scenario *Ehs_His* (implemented National Ecological Network the EHS) compared to *Cur_His* the $A_{0.5}$ decreases from 798 ha to 680 ha (Table 8.2). On the one hand the higher watertables in *Ehs_His* cause a higher counter-pressure on the deeper groundwater, so one would expect a lower $A_{0.5}$ area. But the removal of ditches in *Ehs*-scenarios also means that less of the deep seepage is diverted towards ditches, and more is available for reaching the root zone. Apparently the first mentioned effect has the upper hand.

Creating a buffer zone in the agricultural area (comparison of *Ehs_His* and *EhsBuf_His*) causes only a slight increase of the $A_{0.5}$ area from 680 to 736 ha. But the free meandering of streams (*EhsBufM_His*, see also Section 8.3) causes a substantial increase to 855 ha. The reduced depth of the streams causes this, meaning that less of the deep seepage is directly drawn towards the stream, and more of it reaches the terrestrial riverine vegetation in the stream valleys. Notwithstanding this substantial effect, the seepage to the rootzone is more sensitive to the climatological factors than to the man-made influences. But the seepage is of course not the only determining factor, as will be further explained in Section 9.2 ('Effects on terrestrial ecology').

For the ecological effects the residence times of the seepage are relevant too. The increased fluxes caused by increased precipitation will decrease the residence times. However this mechanism appears to have only a very small effect on the mean 'dimensionless' concentration of calcium as computed with Equation 5.3 (Section 5.) : the mean concentration drops from 0.40 in scenario *Cur_His* to 0.39 in scenario *Cur_HadPi*.

8.3 Effects on the surface water system

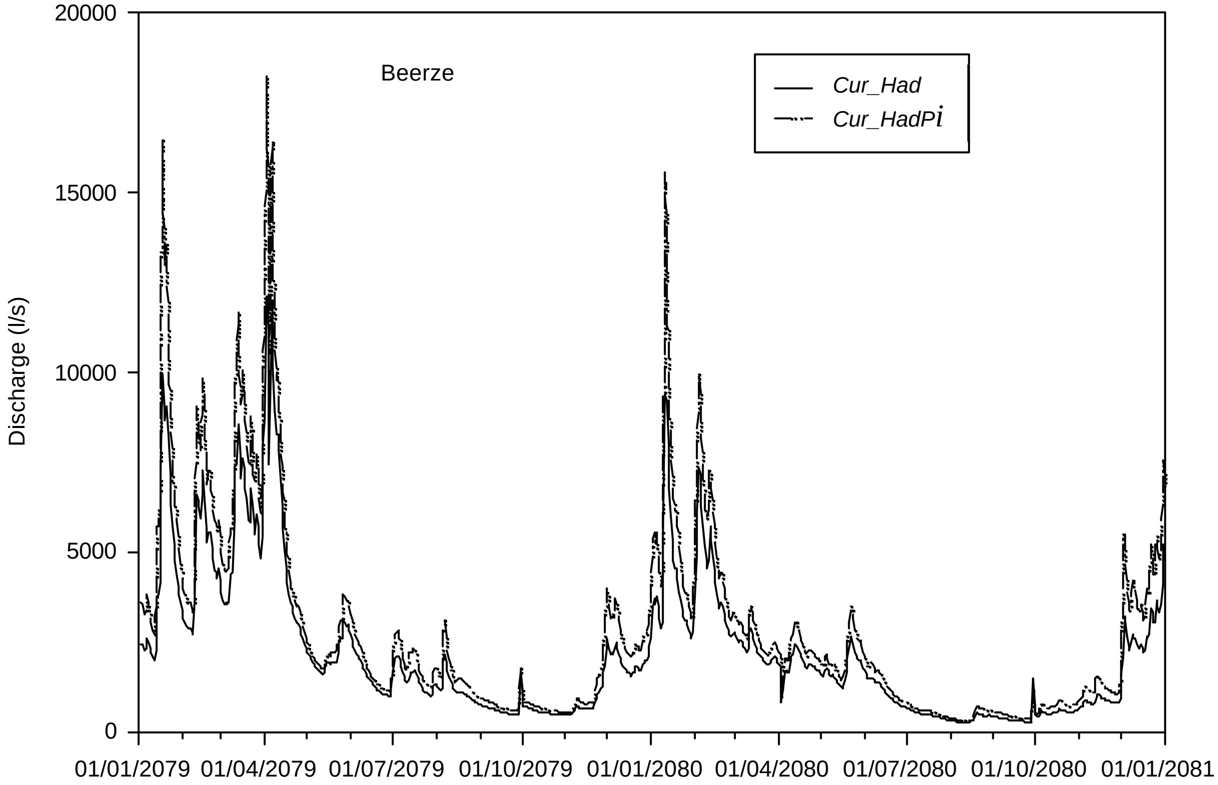
For purposes of dimensioning the surface water system the discharge with a recurrence frequency of 1 year plays an important role in the Netherlands. For the stream morphology the bank-full discharge with a recurrence interval of 1.6 years is relevant (Section 4). For dimensioning based on the most extreme events a recurrence interval of 10 years is often used. Since only 15 years of meteorological data were available for the current situation the results presented in Table 8.3 for extreme discharges are for discharges with a recurrence interval of 5 years. The presented results are for the Beerze, but the ones for the Reusel are comparable if the scenario *Cur_HisPa* is used as a reference (see also Section 2.1). If the results for the Reusel are compared to the current situation (*Cur_His*), then one must take into account that there is a 20% difference of discharge between the current situation (*Cur_His*) and the current situation with averaged precipitation (*Cur_HisPa*).

Table 8.3 Discharge statistics of the Beerze. For comparing results (Δq) *Cur_His* is used as reference. The subscript of q indicates the recurrence interval in years

Scenario code	q_1 (l/s/ha)	$q_{1.6}$ (l/s/ha)	q_5 (l/s/ha)	Δq_1 (%)	$\Delta q_{1.6}$ (%)	Δq_5 (%)
Cur_His	0.44	0.52	0.69	0	0	0
Cur_HisPa	0.45	0.52	0.69	-2	-4	-2
Cur_Had	0.47	0.54	0.68	6	4	-2
Cur_HadPi	0.70	0.80	1.09	58	55	57
Cur_HadEr	0.51	0.58	0.74	16	12	7
Cur_HadPiEr	0.73	0.85	1.16	65	65	68
Ehs_His	0.45	0.52	0.69	2	0	0
Ehs_HadPi	0.70	0.80	1.10	58	55	58
EhsBuf_His	0.45	0.53	0.71	3	3	3
EhsBuf_Had	0.49	0.56	0.74	10	8	7
EhsBuf_HadPi	0.72	0.84	1.18	63	63	70
EhsBuf_HadEr	0.51	0.58	0.77	15	13	12
EhsBuf_HadPiEr	0.74	0.88	1.22	68	71	76
EhsBufM_His	0.45	0.52	0.69	2	1	0
EhsBufM_Had	0.47	0.54	0.67	6	5	-3
EhsBufM_HadPi	0.70	0.80	1.11	58	55	60

As can be seen from Table 8.3 the results for the downscaled Hadley scenario (*Cur_Had*) are very similar to those for the current situation. From the results of scenario *Cur_HadPi* it is clear that the extreme discharges react very strongly to the 17% higher winter precipitation.

Figure 8.3 Simulated discharges of the discharges of the Beerze, for scenario *Cur_Had* (downscaled Hadley) and *Cur_HadPi* with a 17% raised winter precipitation. The plotted values are daily averages of discharges computed with a time interval of 0.025 d.
The sharp drop of the discharge on April 1 is due to the raising of weirs.



This sensitivity is partly caused by the statistical characteristics of the Hadley-precipitation series and partly by the increase of wet zones along the stream valleys. As can be seen from Table 2.5 in Section 2.1.6, the scenario *HadPi* has a more than proportionately higher 10-day moving average than the historic precipitation series: the 10-day moving average increases by 25%, whereas the mean winter precipitation increases by 17%, and the mean yearly precipitation by 10%. This 10-day moving average is known to determine the peak discharges, and not the extreme precipitation events. The reason for this being that the peak discharges involve a build-up of watertables in the streamvalleys, leading to saturated conditions, which generates surface runoff. This build-up is well predicted by the 10-day moving average of the precipitation. That the change of 10-day moving average is so different from the changes of the means is due to the way the series has been generated. It was not generated by transforming the historic series – like is done in many studies – but by modifying a series generated by a General Circulation Model. Analysis on basis of the average precipitation is apparently at fault when making predictions with respect to the peak discharges. In this case the increase of the peak discharge with a recurrence interval of 1 year is double the increase of the 10-day moving average. This still seems a very large increase. That it nevertheless is plausible is due to the influence of shallow watertables on the processes at the soil surface, as is explained below.

When the watertables become very high and reach the drainage base of the shallow trenches and furrows, the flux-discharge relationship given in Figure 3.5 is activated. The inference that this indeed is the mechanism causing the sharp increase of peak discharges is confirmed by the cumulative frequency curves of the Mean Highest Watertables given in Figure 8.1: for the scenario *Cur_HadPi* the area percentage with a MHW higher than 25 cm b.s.s. (the drainage base depth of the trenches) increases from 4.6% in scenario *Cur_His* and *Cur_HisPa* to 7.3% in scenario *Cur_HadPi*. That is a relative increase of 59%, which is virtually the same as the increase of the extreme discharges. The field ditches also play a role, but are far less important: the percentage increase of areas with a Mean Highest Watertable above 1 m b.s.s. (the drainage depth of most ditches) increases from 55% in scenario *Cur_His* to 65% in scenario *Cur_HadPi*. That is a relative increase of only 18%. So the conclusion seems justified that the trenches cause the highly nonlinear effects. It is of course interesting to know whether the computed increase is very sensitive to the assumed drainage resistance of the trenches. At the calibration stage the choice was made to set the resistance at 20 d, whereas a value of 30 d could also have been justified (Section 3.3.4, Figure 3.10). It turns out that a resistance of 30 d affects the discharges of scenario *Cur_His* and *Cur_HadPi* in the same manner, so that the relative increase of *Cur_HadPi* is virtually the same: for scenario *Cur_His* the discharge with recurrence interval of 1 year becomes 0.43 l/s/ha (was 0.44) and for scenario *Cur_HadPi* it becomes 0.68 l/s/ha (was 0.70). In Figure 8.3 an example is given of simulated discharges for scenario *Cur_Had* and *Cur_HadPi*, for a time period involving discharges with a recurrence interval of 1 year and more.

As can be seen from Table 8.3 the simulated land and water use scenarios hardly influence the discharge statistics. Even the free meandering of streams in scenarios *EhsBufM_His*, *EhsBufM_Had* and *EhsBufM_HadPi* has a small impact. Before considering those scenarios, in Figure 8.4 the results are shown for the depth of the stream cross-profile for the current situation and for the situation that the profile is allowed to develop towards the natural dimensions as follows from the calculation method described in Section 4. This natural situation was reached after running the SIMGRO-model three times in an iteration cycle of

Figure 8.4 Depth profiles of stream Reusel, for scenarios *EhsBufM_His* and *EhsBufM_HadPi*

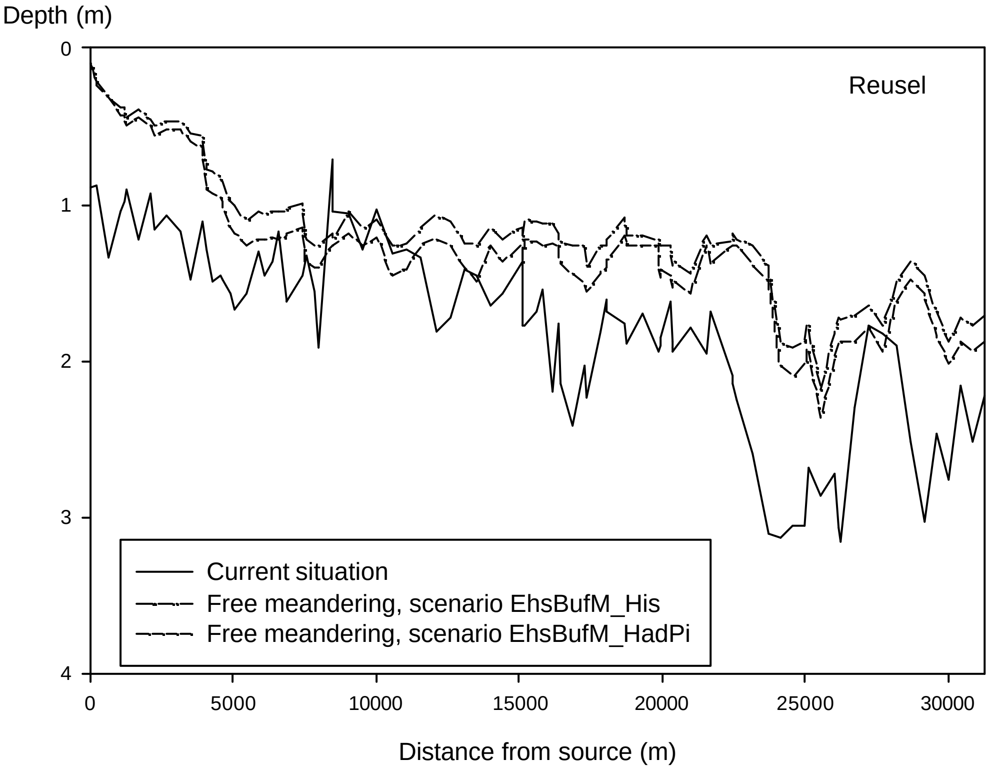
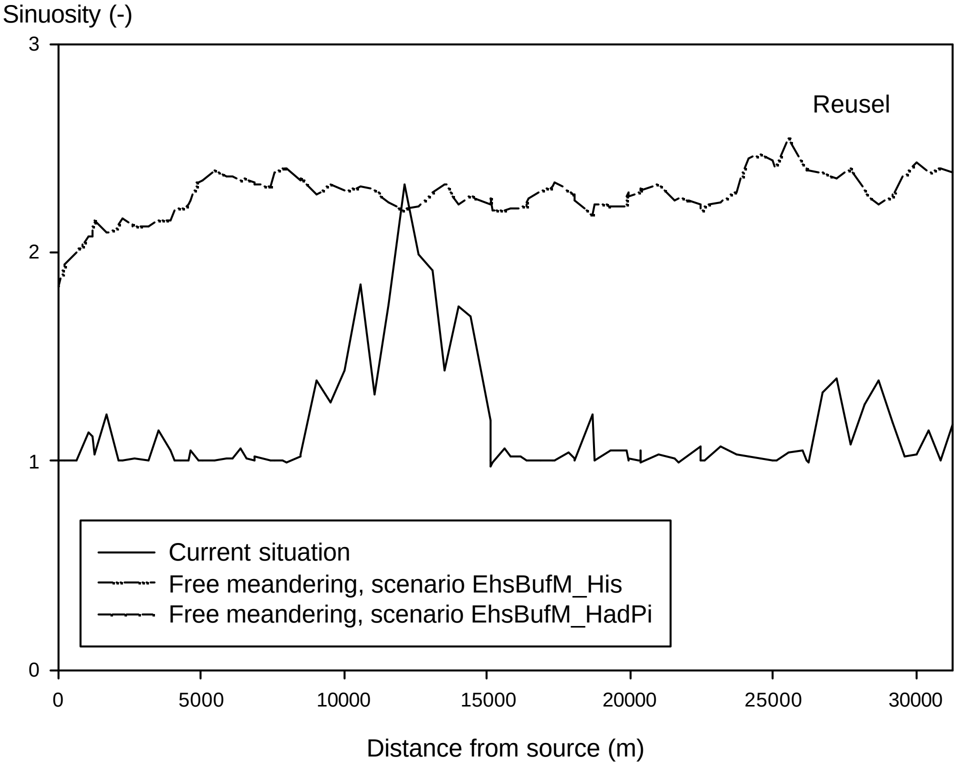


Figure 8.5 Sinuosity of stream Reusel, for scenarios *EhsBufM_His* and *EhsBufM_HadPi*



30-year runs, and each time applying the calculation method. The depth profiles of the stream the Reusel as calculated for scenarios *EhsBufM_His* and *EhsBufM_HadPi* are shown in Figure 8.4.

Figure 8.4 shows a shallow stream depth for the meandering stream. In the Netherlands most streams are dimensioned for a bank-full situation with a recurrence interval of 10 to 100 years. In freely meandering stream systems the bank-full discharge has a recurrence interval of 1.6 years. Therefore the shallow depth for meandering streams could be expected. The difference in depth between the current situation and the meandering situation at the upper part of the stream seems to be higher compared to the middle and lower part of the stream. The over- dimensioning of the upper part of the stream is most likely caused by practical circumstances: the machine that is used for digging the trench has a minimum depth. At a distance of 10 to 15 km from the source the depth of the stream in the current situation is roughly the same as the calculated depth. This part of the Reusel has never been normalized and therefore still has its natural course. The good correspondence between predicted dimensions and actual dimensions gives confidence in the predictions made with the model StreaMES.

The mean sinuosity of the meandering stream is about 2.3. Figure 8.5 shows a slightly increasing sinuosity with increasing distance from the source. Compared to the current situation the sinuosity will roughly increase by a factor 2.

The free meandering involves a substantial reduction of the depth of the stream. That leads to shallow watertables in the stream valleys, and one would expect higher peak discharges. Since that does not appear to happen, there must be a compensating factor at play. The storage in the stream itself does not change much, because on the one hand the storage is reduced by the shallowing of the cross-profile, and on the other hand it is increased by the lengthening of the stream due to the increased sinuosity. The increased sinuosity does still something else, however, and that is the reduction of the water level gradient. It is this factor that makes the stream more sluggish, and thus the stream itself becomes the bottleneck in the discharge process. That in turn causes a backwater-effect in the form of inundations on the soil surface involving the storage of water and a reduced drainage resistance of trenches. But as indicated above, the quick runoff is blocked by the sluggish flow in the stream. In this context it is relevant to mention the way the discharge is computed for water levels above the soil surface of the stream-valley bottom. In the preprocessing of the Q-h relationships the discharge is first computed as if the trapezoidal profile continues above soil surface. Then the value for a certain water level is compared to the bank-full discharge. The difference is multiplied by two and added to the discharge for the considered level. In this manner the model takes into account the extra increase of the discharge capacity when the valley bottom becomes inundated.

9 INDIRECT EFFECTS ON AQUATIC AND TERRESTRIAL ECOLOGY

9.1 Effects on macro-invertebrates

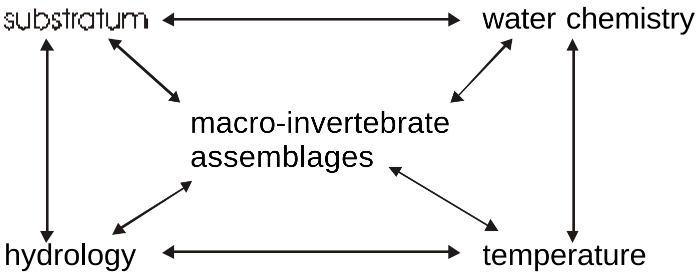
P.F.M. Verdonschot & M. W. van den Hoorn

9.1.1 Introduction

Changes in climate have always occurred. Biological communities endured these changes and either adapted or went extinct. The speed with which changes occurred differed as well as the evolutionary adaptations. Just the last hunderd years man introduced a new mechanism causing a relatively quick change of the climate. Both the rate of change as well as the potential capacity of biological systems to get adapted are yet unknown.

About the relationship between discharge pattern and macro-invertebrate communities in lowland streams little is known. Even less known are the effects of changes in hydrology of the catchment on the lowland stream ecosystem. The most important and most indicative organism group in lowland streams are the macro-invertebrates. In a natural stream they compose the larger part of the ecosystem and generalists as well as specialists occur. A high number of taxa inhabit the streams and all differ in sensitivity to different ecosystem components (Figure 9.1). This makes the macro-invertebrates well suited to be used as indicators for quality, in this respect as indicators of hydrological quality or in other words discharge regime.

Figure 9.1 The simplified relationship between macro-invertebrates and the stream environment (adjusted after Cummins & Lauff 1969).



In our study the streams did not differ in water chemistry. The substrate relationships are discussed in Chapter 6. From that it appeared that substrate and hydrology could be exchanged as explanatory variables though both could not explain the other. In this chapter the interactions between macro-invertebrates and hydrology is elaborated. This means an acceptance of a strong relation between substratum and hydrology which is not yet further unravelled.

The objective of this study is to establish a robust relationship between discharge regime and macro-invertebrate communities. A relationship which can be used as a tool to assess the effect of changes in the climate through changes in hydrology on the natural lowland stream community.

9.1.2 Materials and methods

Metrics

Constrained ordination analysis resulted in a major gradient between small 'high and low discharge average ranges' at one side of the gradient versus wide 'high and low discharge average ranges', in other words high peaks at one side and constant discharge on the other. This gradient runs almost along the first ordination axis which indicates the high importance of this factor. Thus 'high and low average discharge ranges' are strongely related to the distribution patterns of macro-invertebrates in our studied streams. To refine this relationship the macro-invertebrate samples of our ten studied streams were translated into the following more general metrics:

- stream velocity index (v-index; Tolkamp & Gardeniers 1977)
    description: This index represents the rate of rheophily of the macro-invertebrate taxa per sample. The rate of rheophily is expressed in five classes, running from class one referring to stagnant water taxa (limnetic taxa) up to class five referring to taxa solely occurring in (fast) running water (rheobionts).
    rationale: The more natural a stream is, the more rheophilic taxa will be present, thus the index score will be higher.
- diversity index (H'-index; Shannon & Weaver 1949)
    description: This index represents the diversity in taxon composition of a sample.

rationale: The more natural a stream is, the higher the diversity score will be until an optimum in a near-natural stream is reached. A slight disturbance in a pristine stream leads to an increase in diversity, while a further disturbance will result in a drop in diversity. From the optimum diversity (under slightly disturbed conditions) on, the diversity index will decrease towards a pristine condition. As in this research only natural and near-natural streams were sampled the index will decrease along a gradient towards the most natural conditions studied.

- rarity-index (r-index)

  description: This index represents the rate of rare taxa present in a sample. The rarity-index is expressed in five classes from class one referring to very common taxa up to class six referring to very rare taxa.

  rationale: The more natural a stream is, the more rare taxa will occur, thus the index score will be higher.

- saprobity index (s-index; Sladecek 1973)

  description: The saprobity index represents the saprobity rate indicated by the macro-invertebrate taxa per sample. The saprobity rate is expressed in five classes from class five referring to oligosaprobic taxa up to class one referring to taxa solely occurring in polysaprobic waters (saprobionts).

  rationale: The more natural a stream is, the more taxa indicating oligosaprobic conditions will be present, thus the index score will be higher.

To calculate an index-score all taxa were as much as possible classified into the respective classes that compose the specific index. All indices, except for the diversity, are calculated according to the formula:

$$index\ score = sum\ (t_i * n_i) / sum\ (n_i)$$

in which:

- t_i : indicative weight of taxon i in the sample
- n_i : total number of individuals of taxon i in the sample

All but one index increases in score when streams become more natural.

Of special interest for this study is the discharge dynamics index (DDI). In a natural lowland stream the retention capacity of the catchment is capable of ‘absorbing’ the rain water deposition and then releasing this water slowly to the stream. Thus a natural stream will show a stable discharge pattern without high peaks or low drops in discharge. With this rationale on natural discharge regime, discharge dynamics were translated into the discharge metric DDI. It represents the rate in discharge dynamics indicated by continuously measured discharge data over one year in a stream. Discharge dynamics were translated into five classes ranging from class one for the most extreme discharge events to class five for the most constant discharge periods. In formula it is given by:

$$DDI = sum\ (R_i * s_i) \ / \ sum\ (R_i)$$

in which

- s_i : indicative weight per discharge dynamic class (i=1…5)
- R_i : total number of scores in the repective discharge dynamics class R

The index runs from 5 for a very constantly discharging stream towards one for a very dynamic stream.

Statistical testing

To test whether the assumptions about biological and hydrological metrics and their mutual relationships are correct, the data for the ten studied streams were used. Each of the biological indices is plotted against the DDI, the trendline is indicated in the plot and the R-square is calculated (linear regression analysis).

Scenarios

The different scenarios - listed in Table 2.7 - were tested. The current climate condition is taken as the reference.

9.1.3 Results

All four biological metrics were calculated for each of the studied streams and plotted against the discharge dynamics index (DDI). Trends between stream velocity (Figure 9.2), saprobity (Figure 9.3), rarity (Figure 9.4) and diversity (Figure 9.5) were indicated in the respective plots.

Figure 9.2 Trend between stream velocity index (v-index) and discharge dynamics index (DDI).

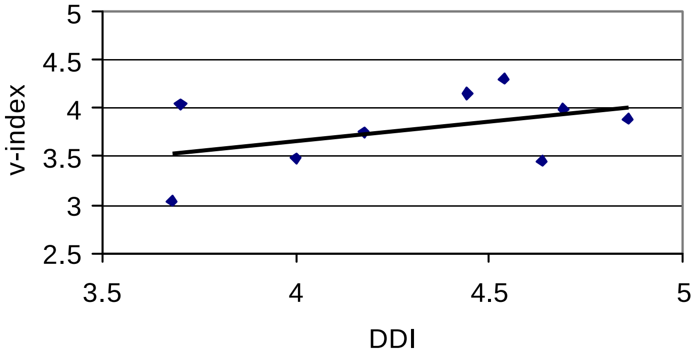


Figure 9.3 Trend between saprobity index (s-index) and discharge dynamics index (DDI).

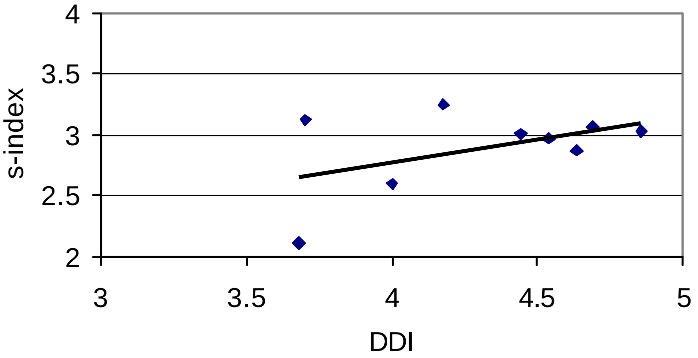


Figure 9.4 Trend between rarity index (r-index) and discharge dynamics index (DDI).

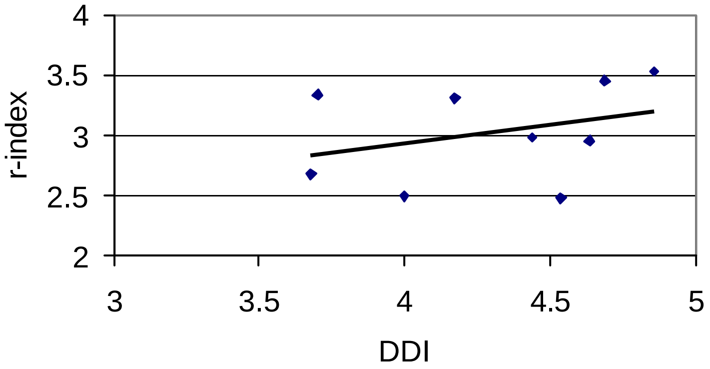


Figure 9.5 Trend between diversity (H-index) and discharge dynamics index (DDI).

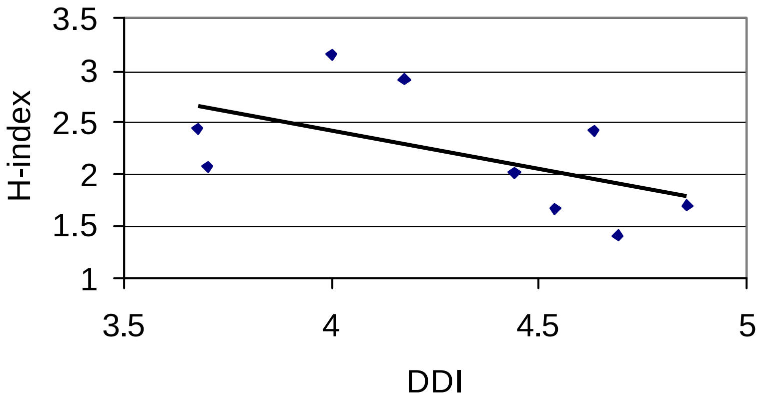


Table 9.1 R-square values for each the biological metrics.

DDI tested against:	R-square	R-square minus Springendal stream South
stream velocity index	0.19	0.45
saprobity index	0.22	0.54
diversity index	0.31	0.49
r-index	0.10	0.32

Using all data the plots showed a clear trendline but the R-square values were very low (Table 9.1). It turned out that one of the streams, Springendal stream South, had a high DDI but still was inhabited by a reasonably well developed natural stream community. This extraordinary condition can be explained by two possible causes:

1. The Springendal stream South is fed by deep groundwater and despite occasional discharge peaks, caused by drainage of part of the upper catchment, a very constant base flow is guaranteed. Furthermore, though the main channel receives drainage water from small agricultural enclaves in the upper catchment, the channel is also accompanied by a number of side springs and small side tributaries (short, small upper courses), both ensuring a constant input of sensitive and characteristic taxa.
2. The Springendal stream South is a smal tributary in a network of two main tributaries (the other is the Springendal stream North) and another three less important ones. Except for Springendal stream South all these tributaries are near-natural. These tributaries guarantee a constant input of biological material (eggs, larvae, etc.) into another tributary.

Therefore, Springendal stream South was left out of the statistical testing series (Table 9.1). This shows a raise of the R-square value to about 50%, except for the rarity index. The r-index does not seem to be suitable and should be investigated further. A R-squared value of around 50% is not high but for the limited number of eight streams and with the knowledge that also other parameters like substratum influence the macro-invertebrate distribution, a percentage of 50% nevertheless indicates a positive correlation. Therefore, it is concluded that the biological metrics support the DDI as a measure of hydrological quality in the studied streams. The higher the DDI score is, the more natural a stream will become.

9.1.4 Scenario Testing

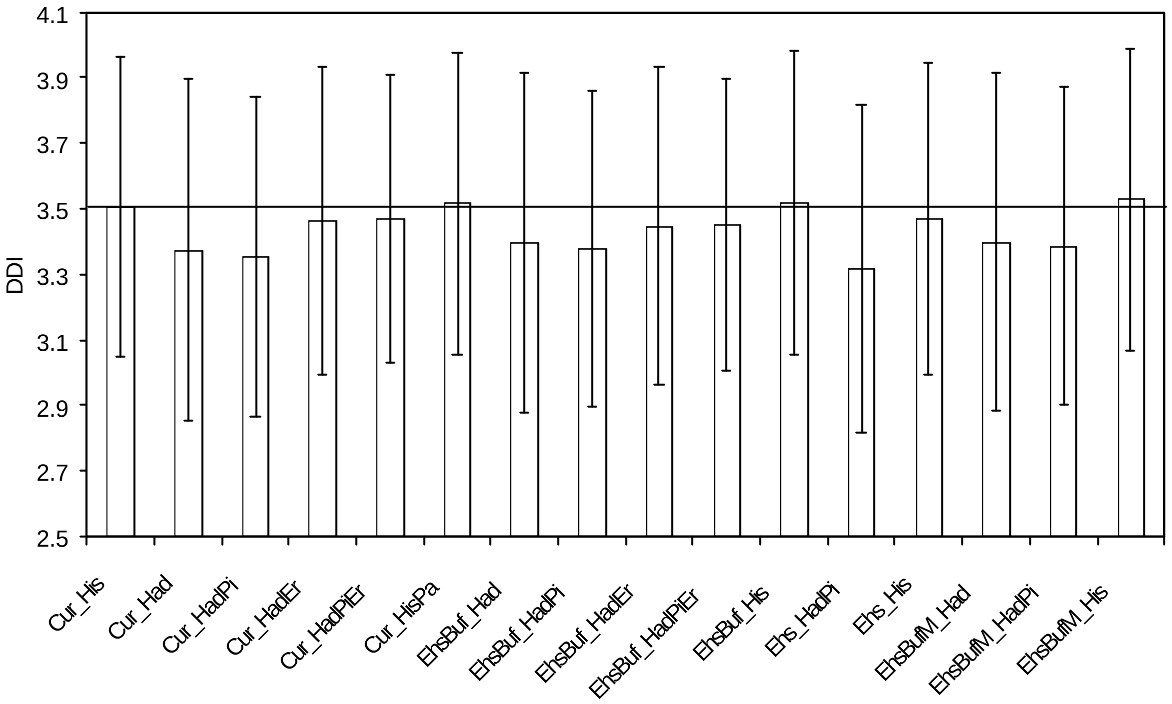
The DDI was used as a measure for the naturalness of (small) upper to middle courses of lowland streams. For each of the scenarios the DDI was calculated for the years 1998 and 2100. About 1400 sites within the test area, the catchment of Beerze-Reusel, were suited to be included in the scenario study. In total 16 scenarios were tested (Table 9.2). The results for the catchment under study were summarized by calculating the average and standard deviation of DDI-scores over all the sites (Figure 9.6). The differences in average index score were tested (Table 9.2).

The average discharge dynamics score differs for most of the scenarios significantly from the reference (current condition), even though the value of the average index only differs slightly.

Table 9.2 Significance of differences between scenarios (for scenario codes see Table 2.7).

scenario	average DDI	sd DDI	number of dry sites		P-value	significance
Cur_His	3.47	0.44	417			reference
Cur_HisPa	3.52	0.46	515	+98	0.703	ns
Cur_Had	3.51	0.46	508	+91	0.000	***
Cur_HadPi	3.37	0.52	605	+188	0.000	***
Cur_HadEr	3.35	0.49	493	+76	0.045	*
Cur_HadPiEr	3.46	0.47	509	+92	0.061	ns
Ehs_His	3.52	0.46	495	+78	0.642	ns
Ehs_HadPi	3.40	0.52	595	+178	0.000	***
EhsBuf_His	3.38	0.48	480	+63	0.000	***
EhsBuf_Had	3.45	0.48	520	+103	0.006	**
EhsBuf_HadPi	3.45	0.44	426	+9	0.009	**
EhsBuf_HadEr	3.47	0.48	511	+94	0.096	ns
EhsBuf_HadPiEr	3.32	0.50	488	+71	0.000	***
EhsBufM_His	3.53	0.46	487	+70	0.361	ns
EhsBufM_Had	3.40	0.51	580	+163	0.000	***
EhsBufM_HadPi	3.39	0.48	477	+60	0.000	***

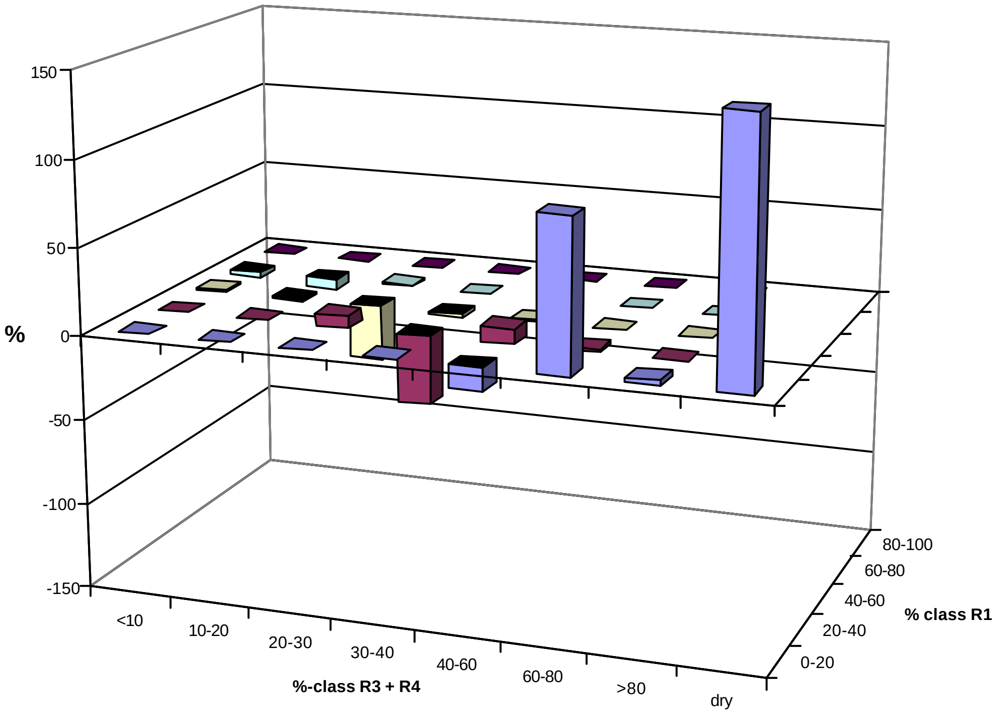
Figure 9.6 Average and standard deviation of DDI score per scenario (for codes see Table 9.2).



The scenarios which resulted in a significantly different score all show a decrease in the index. Under all these scenarios the climate change shows a significantly negative effect on the stream community. Also looking at the sites which dry up for a longer period of time (Table 9.2) it appears that all scenarios show an extended number of desiccated sites. Desiccation is fatal for most stream communities. All scenarios show an extended drought effect in the catchment.

Comparing the current condition with the implemented ecological infrastructure (*Ehs*), the EHS and buffer zone of extensive grassland (*EhsBuf*) and the EHS and buffer zone and free meandering main streams (*EhsBufM*), it is concluded that nor the ecological infrastructure, nor the buffer zone nor the meandering main stream affect the discharge dynamics index. This does not mean that especially the latter will not affect the macro-invertebrate community. On the contrary it will have a major effect but this parameter is not included in the hydrological quality assessment.

<u>Figure 9.7</u> Differences between the current climate condition (*Cur_His*) and the most dynamic climate condition (*Cur_HadPi*) in percentage of sites which change of discharge dynamics class between both scenarios.



Looking in more detail at the most dynamic scenario (*Cur_HadPi*) the scores for this scenario for discharge dynamics class R_1 were classified in percentages and plotted against the sum of scores for classes with the sum of R_3 and R_4. In this plot results show the percentage changes of sites in comparison to the current climate condition (*Cur_His*) (Figure 9.7). The percentage of sites which are classified into a more extreme discharge class (R_3R_4 %-class 60-80) increase strongely, indicating the increase in dynamics under this scenario. Also the number of sites with an extended period of drought strongely increases (Figure 9.7).

9.1.5 Discussion

The response of the macro-invertebrates to extreme flow events and their ability to recover are shown to be related to the discharge dynamics index. Using stream velocity, saprobity, rarity and diversity as measures for the degree of development of the stream community, they all – except for rarity – show a correlation with discharge dynamics. These trends support the importance of discharge regime on community development. With this tool changes in climate resulting in changes in hydrology could be used to predict ecological effects. Climate change leads, in most scenarios, towards a worsening of the ecological circumstances in (small), soft-bottomed lowland streams.

9.2 Effects on terrestrial ecology

J. Runhaar

9.2.1 Introduction

As indicated in Chapter 7 the present area of wet and very moist riverine grasslands is very limited, as a result of intensified farming and changes in land use and water management. Therefore the present situation is not very suited to be used as a reference for the effects of climatic change. Instead, a hypothetical reference situation has been used (scenario *EhsBuf_His*, with current climate, see section 2.2). In this reference the plans for the enlargement of the area of nature areas[3] have been implemented, and the water management in and around the nature conservation areas has been adapted to create conditions more favorable for the realization of wet mesotrophic grasslands. In order to put the effects of climate change into perspective, the effects of land- and watermanagement measures are discussed first in the following section. Subsequently, in Sections 9.2.3, 9.2.4 and 9.2.5 the predicted effects of climate change are elaborated upon.

9.2.2 Effects of management measures

Figure 9.8 shows the effects of changes in nature management and water management on riverine grasslands. The effects are presented in terms of changes in the area of wet to moist (mesotrophic) riverine grasslands. For the definition of the riverine grassland types see Table 7.7. The blockdiagram to the left (*Cur_His*) gives the (predicted) area of wet and moist riverine grasslands in the Beerze-Reusel area in the current nature conservation areas. As already mentioned in Section 2 the area of these grasslands, which are the most interesting from a nature conservation viewpoint, is very limited (see Figure 9.9 for their present distribution). The area predicted with NATLES is 63 ha (15+48), which may even be an overestimation of the present area. In the near future the area under nature management is expected to strongly increase with the realization of the National Ecological Network (EHS).

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[3] The realisation of the so-called National Ecological Network, according to the plan by the Ministry of Agriculture, Nature and Fishery, 1990; in this report the National Ecological Network is referred to as the 'EHS', using the Dutch abbreviation.

The second blockdiagram in Figure 9.8 shows an increase in wet and very moist riverine grasslands from 63 to 163 ha (53+110) owing to the increase of areas under nature protection, assuming that no changes in water management occur, neither within the areas or outside of them.

The latter assumptions are rather unrealistic, as the present water management has been tuned to maximizing agricultural production. Because nature management aims at increasing the area of wet riverine grasslands, measures will no doubt be taken that are aimed at raising the surface water levels and watertables. Reduced drainage within the EHS areas in scenario *Ehs_His* is expected to increase the surface area of wet and very moist riverine grasslands from 163 to 219 ha (219=81+138, Figure 9.8).

Figure 9.8 Effects of changes in nature management and surface water management on the area (ha) of wet and moist riverine grasslands.

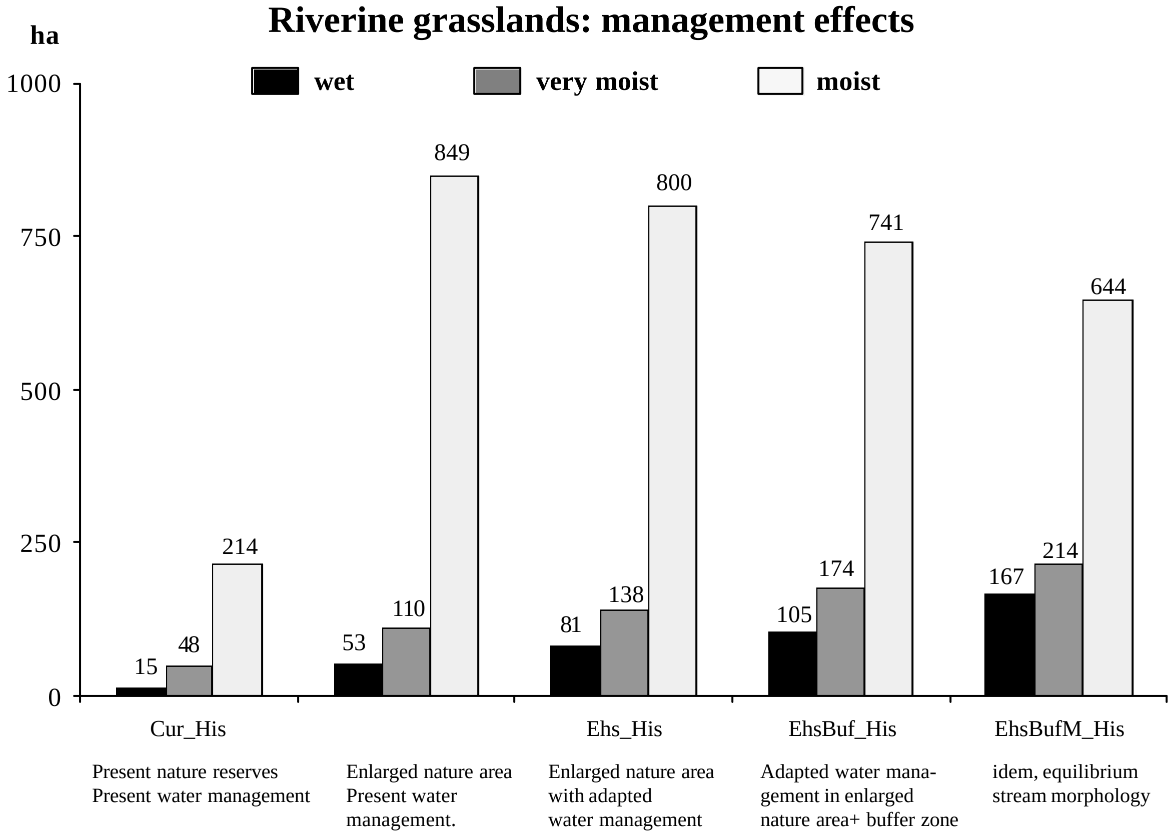
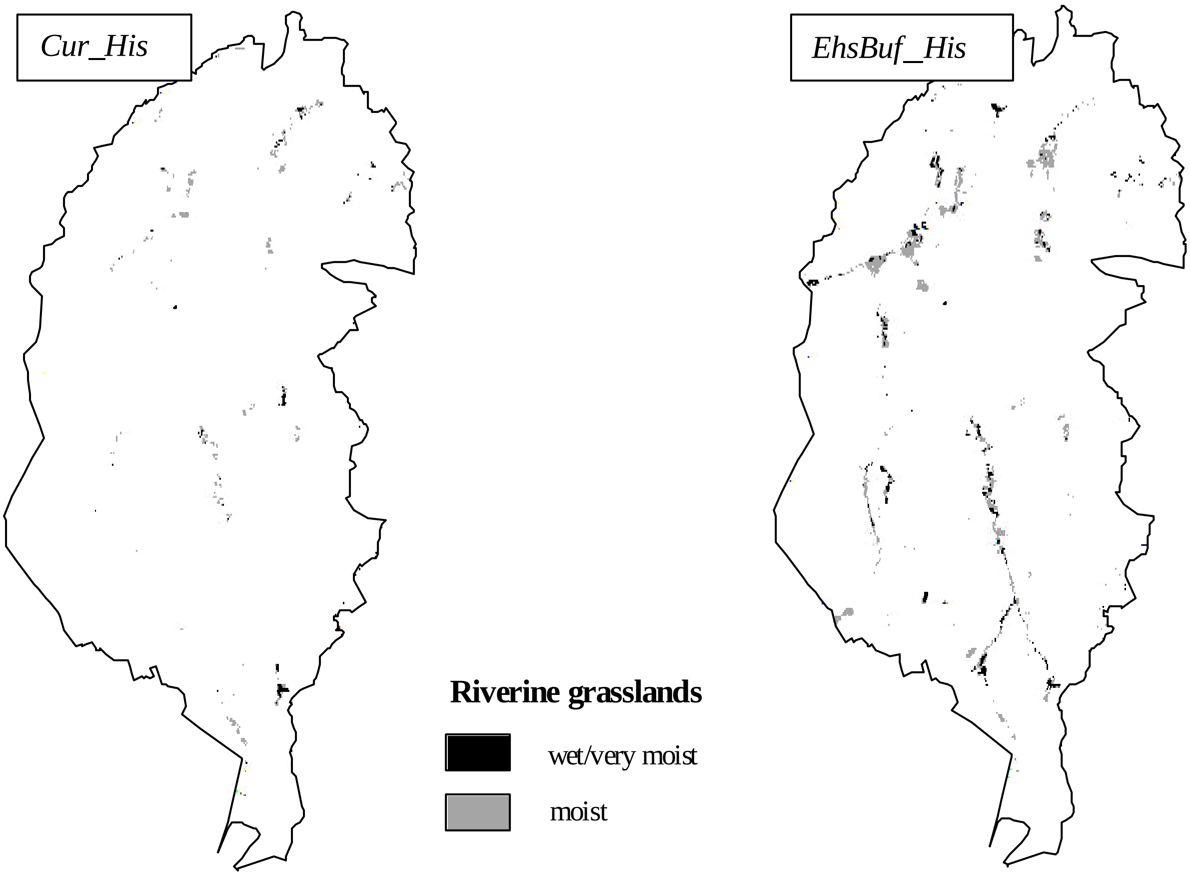
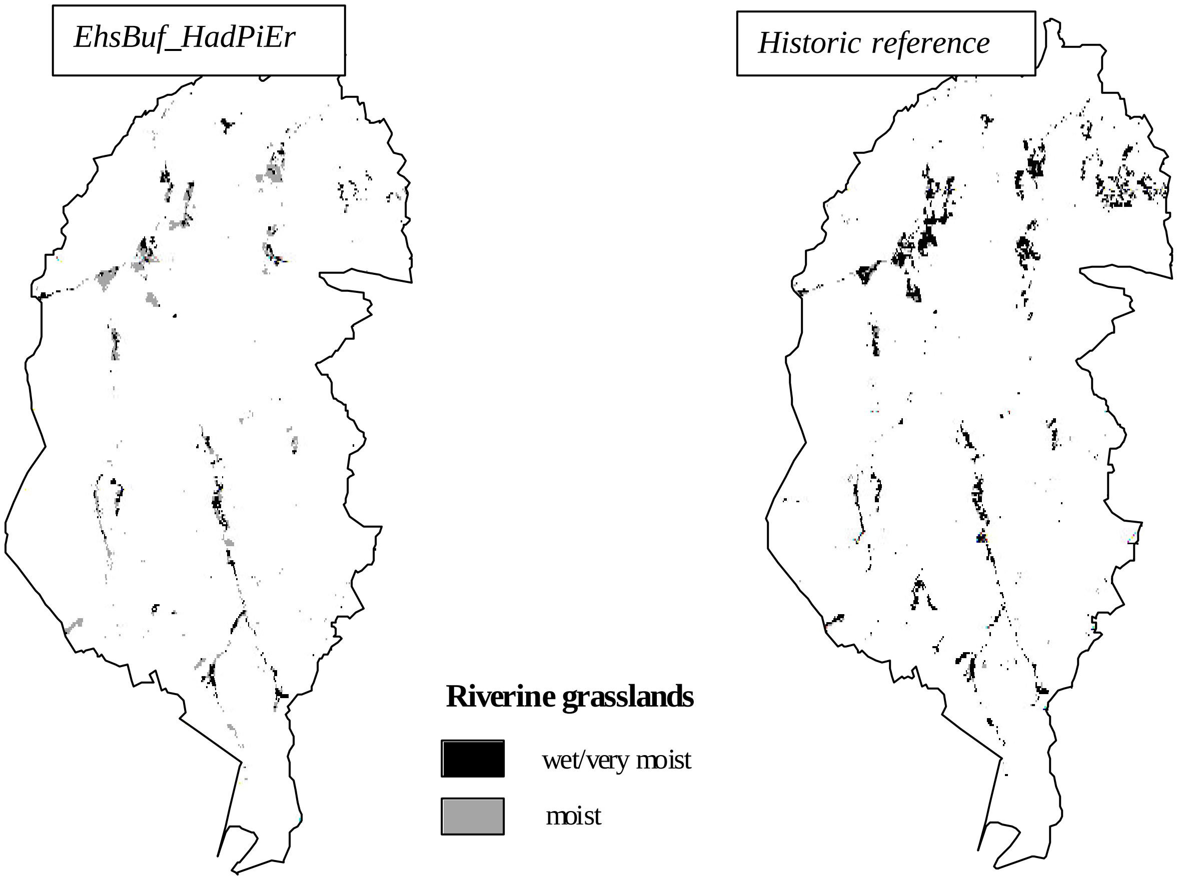


Figure 9.9 Impact of nature conservation measures. To the left the predicted distribution of wet and moist riverine grasslands with present hydrology and present nature conservation areas. To the right predicted situation after realization of the National Ecological Network and with adapted water management in and around nature conservation areas



Reduced drainage in a buffer zone around the EHS nature reserves will result in an additional increase with 70 ha, to 279 ha (*EhsBuf_His*, 279=105+174,see Figure 9.8 and also Figure 9.9 for the spatial distribution). The largest increase in the area of wet and very moist riverine grasslands can be achieved when additionally sedimentation and erosion processes are allowed to bring about a new river morphology, that is in equilibrium with the river discharge (*EhsBufM_His*). Because of the decreased river depth in this situation the draining effect on the adjoining riverine grasslands will decrease. The result is an additional increase with 102 ha, to 381 ha (167+214, see Figure 9.8).

Figure 9.10 Distribution of wet and moist riverine grasslands in the wettest scenario (*EhsBuf_HadPiEr,* see Section 9.2), compared with that in a scenario with historic hydrology as estimated by Van Ek et al. (1997) on the basis of soil characteristics and relief.



To get an impression of the impact of man-induced changes a calculation was made for a situation with a historic reference hydrology, as estimated by Van Ek *et al.* (1997) on the basis of soil type, relief and historical land use (Table 9.3, Figure 9.10). In the historic reference situation according to Van Ek et al. wet riverine grasslands prevail (MSW 0-25 cm below soil surface), whereas in the other scenarios, even with adapted water management and with the wettest climate scenario (*EhsBuf_HadPiEr* in Figure 9.10), moist grasslands are most common (MSW > 40 cm below soil surface). Reasons for this discrepancy may be that (1) Van Ek *et al.* have overestimated the area of wet upward seepage areas, or (2) that in this study the drainage in the scenarios with adapted water management is still more intensive than in the past situation, or (3) that deep extraction wells in the northern half of the study region have a strong effect. These wells were not present in the historic situation, or only with a much smaller extraction rate. The latter explanation (3) is thought to be the most likely one.

Table 9.3 Area of wet and very moist riverine grasslands with present hydrology, compared with situation with reference hydrology as estimated by Van Ek *et al*. 1997.

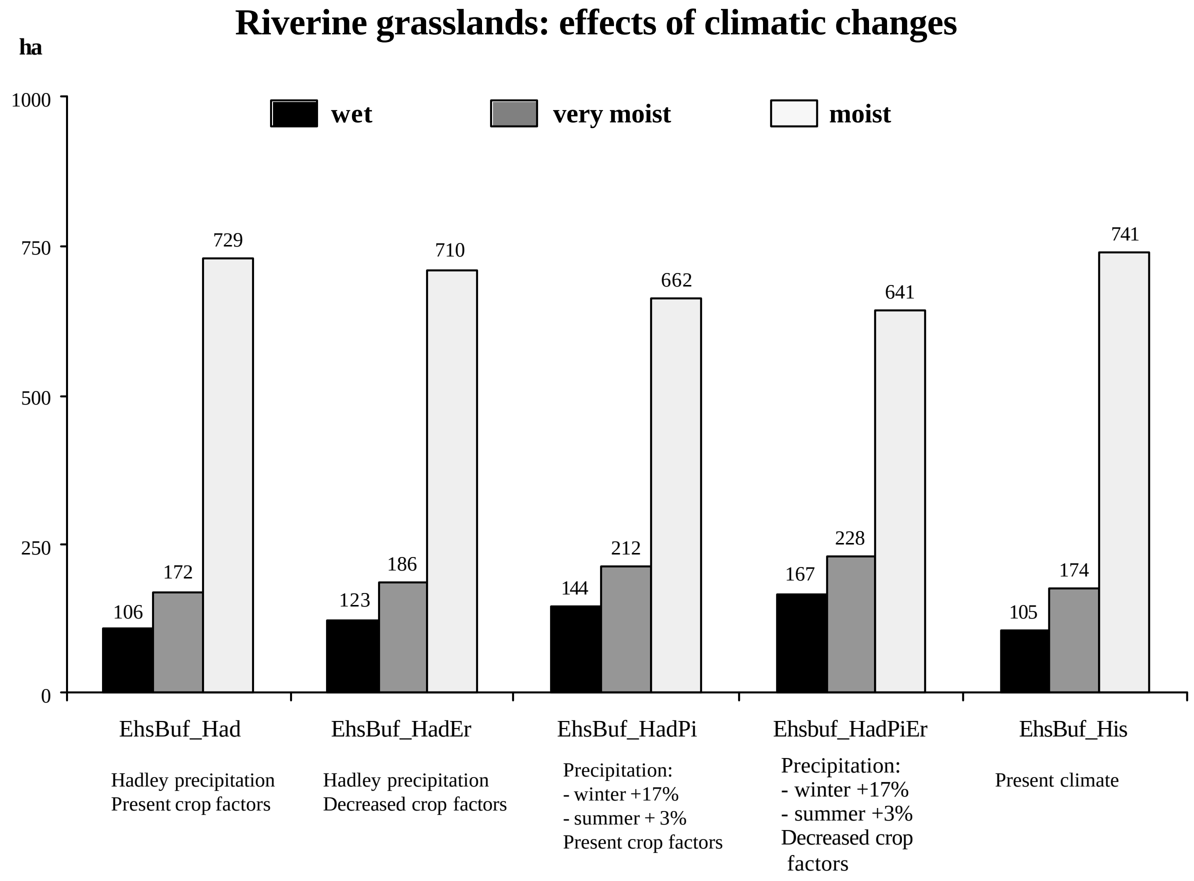
	present nature area	planned nature area (EHS)
present hydrology	63	163
reference hydrology	-	1200

9.2.3 Effects of climate change on areas of wet riverine grasslands

Figure 9.11 shows the effects of changes in climatic conditions on the area of wet and dry riverine grasslands. For comparison purposes the effects of changes in climatic conditions on the area of wet and dry heath is shown in Figure 9.12. The situation in which the EHS has been realized and drainage in the EHS and surrounding buffer zones has been reduced (*EhsBuf_His*) is used as a reference situation for the present climate (diagram on the far right). The first two diagrams show the changes in the area of riverine grasslands under the Hadley climate scenario (*EhsBuf_Had* and *EhsBuf_HadEr*, the former with present crop factors, the latter with decreased ones). The next two diagrams show the changes in the area of riverine grasslands under the scenarios *EhsBuf_HadPi* and *EhsBuf_HadPiEr* in which the temperature increase is equal to that in the Hadley scenario, but the annual precipitation increases more strongly (17% increase in the winter; see Section 2.2).

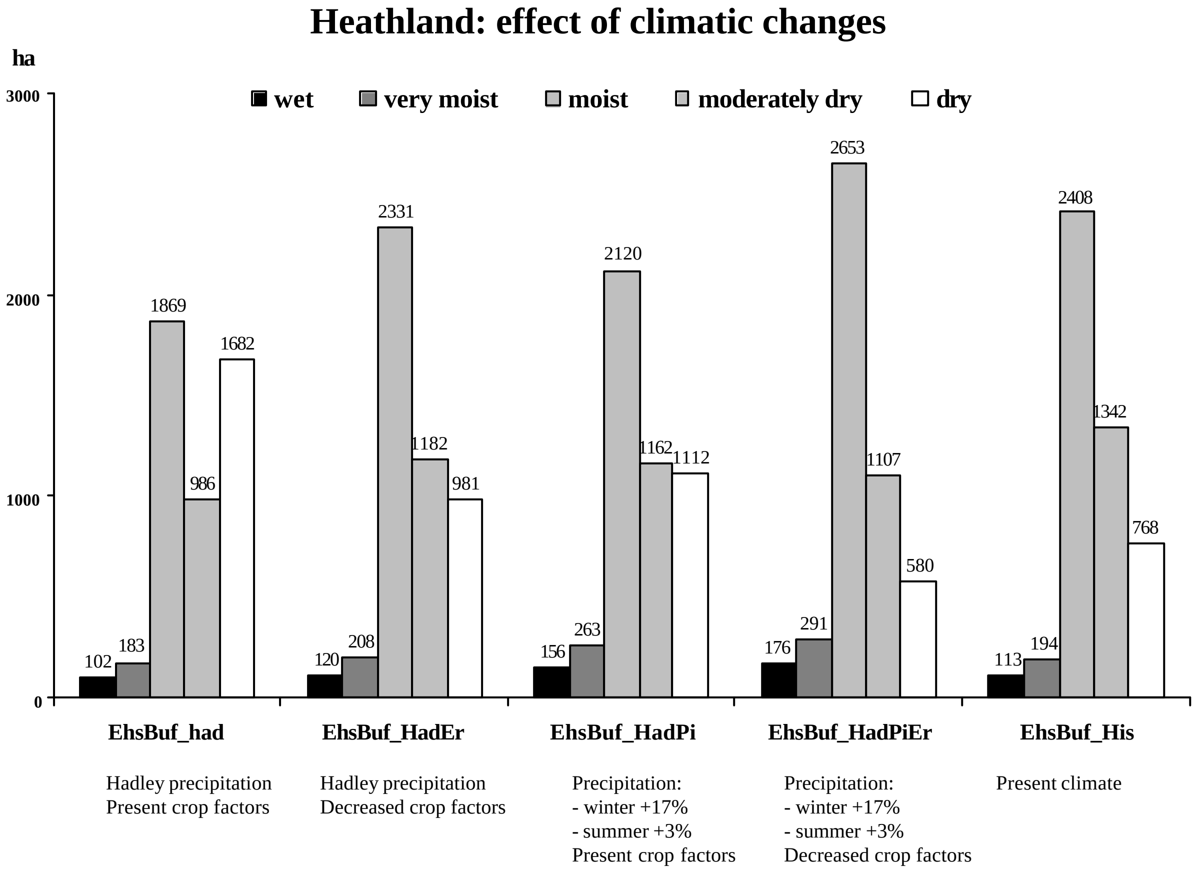
Under the Hadley scenario when no changes in crop factors are assumed (*EhsBuf_Had*) the precipitation excess will decrease. In the upland infiltration areas there are substantial shifts in moisture regime, resulting in a shift from moist to dry heathlands (Figure 9.12). Dry heath increases by 119 % from 768 to 1682 ha. This is caused by lower summer watertables, which causes more moisture stress for the vegetation. Compared to the effects on the upland infiltration areas, the effects on wet riverine grasslands are moderate. The *EhsBuf_Had* scenario hardly differs from the reference situation *EhsBuf_His*: the area of wet riverine grassland is predicted to be 105 ha in the former and 106 ha in the latter.

Figure 9.11 Effects of changes in climatic conditions on the of area of wet and moist riverine grasslands.



In the situation that the crop factors are reduced because of the decreased transpiration under CO_2-rich conditions (*EhsBuf_HadEr*) the precipitation excess increases. In ‘wet’ parts of the the infiltration areas there is a slight increase in the area of wet heathland (+ 6%, from 113 to 120 ha), but also a more pronounced increase in the area of dry heathland (+18%, from 768 to 981 ha). All in all, this scenario leads to a more pronounced contrast in the infiltration areas between wet and dry situations, and a decrease in the area of moist heathland. The effect of decreased crop factors in *EhsBuf_HadEr* on the relative areas of wet, moist and dry riverine grasslands are moderate but not insignificant: the area of wet riverine increases from 105 to 123 ha.

Figure 9.12 Effects of changes in climatic conditions on the of area of wet and dry heath



In the infiltration areas the contrast between wet and dry situations increases in a most pronounced manner in the *EhsBuf_HadPi* scenario. In this scenario the winters are much wetter because of increased precipitation, while in summer the increased temperature leads to increased evaporation. In this scenario both wet and dry heathlands increase in size (from 113 to 156 ha and from 768 to 1112 ha, respectively), whereas the area of moist and moderately dry heathland decrease from respectively 2408 and 1342 ha to respectively 2120 and 1162 ha (Fig. 9.12). In the riverine grasslands the effects of this climate scenario are less pronounced (Fig. 9.11). The total area of wet and moist riverine grasslands remains the same, but there is a shift towards wet grasslands (an increase of the latter from 105 to 144 ha).

The *EhsBuf_HadPiEr* is by far the ‘wettest’ scenario as in this scenario the precipitation strongly increases, whereas the evaporation hardly increases because of lower crop factors. In the infiltration areas this is accompanied by a shift from dry and moderately dry heathland to moist heathland (e.g. a decrease from 768 to 580 ha for dry heathland and an increase from 2408 to 2653 ha for moist heathland). The area of wet riverine grasslands and wet heathlands increases significantly. In the river valleys there is a similar shift from moist grasslands (-100 ha) towards wet and very moist grasslands (+116 ha)(Figure 9.11).

The total area of wet, very moist and moist riverine grasslands is more or less the same in all scenarios (1020 ha), the largest changes being a 1% decrease in the driest scenario *EhsBuf_Had*. This is seemingly in conflict with the observation in Section 8.2 that in the climatic scenarios *Cur_Had* and *Cur_HadPi* there is a strong increase in the area with upward seepage. In climate scenario *Cur_HadPi*, with increased precipitation, an increase in the area of mesotrophic riverine grasslands was expected, due to the buffering effects of bicarbonate-rich groundwater. An analysis of the results shows two reasons why in scenario *EhsBuf_HadPi* the area of wet and moist riverine grasslands nevertheless remains the same. In the first place, the increase in upward seepage is to a large extent situated in places with non-calcareous groundwater according to the data of Van Ek *et al.* (1998), so that increased seepage does not result in increased buffering. In an additional scenario, in which all groundwater in the study area is assumed to be bicarbonate-rich, there is an increase in the area of wet and moist riverine grasslands due to the increase in seepage (Table 9.4, second column). However, the increase is relatively small (+3%). This is caused by the fact that increase in upward seepage often occurs in mineral-rich river valley soils, which are already buffered or have a higher base saturation and are only weakly acidic. In these places increased seepage does not lead to changes in ecosystem type (wet and moist riverine grasslands). A much stronger effect can be expected in situations where groundwater is uniformly bicarbonate-rich and in which all soils are non-calcareous. In that scenario the increase in the

Table 9.4 Area of wet and moist riverine grasslands (ha) in the scenarios *EhsBuf_His* and *EhsBuf_HadPi* compared with situations in which (a) groundwater in the whole study area is assumed to be bicarbonate-rich, and (b) groundwater is assumed to be uniform bicarbonate-rich and all soils are assumed to be non-calcareous.

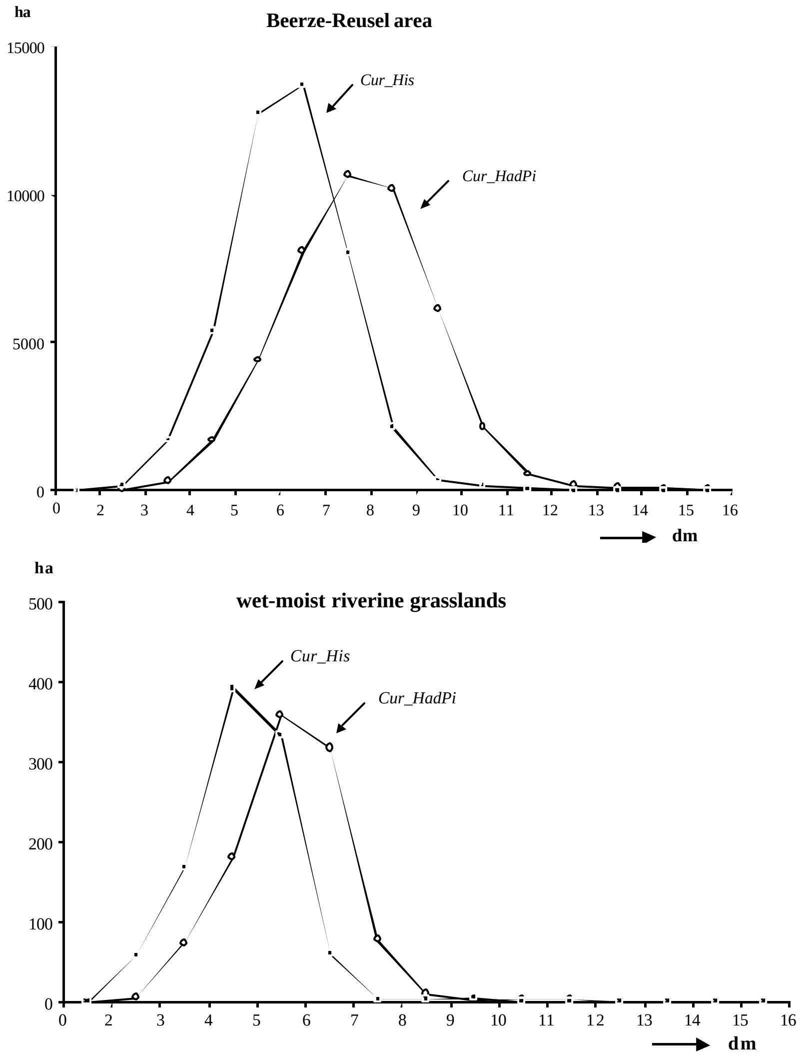
Scenario:	standard scenarios (*EhsBuf_His* and *_HadPi*)	bicarbonate-rich groundwater (a)	bicarbonate-rich groundwater, non-calcareous soils (b)
EhsBuf_His	1020	1052	343
EhsBuf_HadPi	1018	1079	405

area of wet and moist riverine grasslands is more or less in line with the increase in upward seepage (an increase with 18%, see Table 9.4, third column). In the long term the increase in upward seepage in these soils may form an efficient buffer against the decalcification that will occur under infiltration conditions. The *buffering* capacities of the soils are *over*estimated in NATLES. In this model, soil acidity is predicted for present soil types for a period of 10-30 years. In this study predictions are made for a much longer period (about 80 years), in which leaching may lead to a lower buffering capacity of the soil. Therefore buffering with bicarbonate-rich groundwater may become even more important than in the present situation.

9.2.4 Effects of climate change on moisture dynamics

As indicated in Section 7.2, dynamic situations in which both pronounced anaerobic periods and periods with moisture stress occur on the same site are very rare in the present climate. However, the climatic changes may result in more extreme situations. This is most likely to occur in the climate scenario *Cur_HadPi*, in which both the winter precipitation and the summer evaporation increase (downscaled Hadley scenario, and increased precipitation by KNMI rule-of-thumb). In this scenario the watertable fluctuations increase, with about 0.2m in the whole area, and about 0.1m in wet and moist riverine grasslands (Figure 9.13). A hypothesis in this study was that a new and more dynamic habitat might come into existence, with both anaerobic conditions due to high groundwater levels in winter and drought stress in summer due to lower groundwater levels in summer and increased evaporation. However, this turns out to hardly be the case. Table 9.5 shows that even in the climate scenario *HadPi* moisture stress is not expected to occur in the wet and very moist riverine grassland. Only in the heathland vegetations there is a small increase in wet and very moist heath with little or moderate moisture stress (respectively 3-13 days and 14-30 days with a soil water potential less than -12m). Wet and very moist sites with large moisture stress (>30 days with a soil water potential less than -12m) are absent in both the present and the predicted situation.

Figure 9.13 Groundwater fluctuation (difference between Mean Spring Watertable and Mean Lowest Watertable) in the current climate and in the climate scenario *Cur_HadPi.* Hectares per groundwater fluctuation class. Above: groundwater fluctuations in the whole study area. Below: groundwater fluctuations in wet and moist riverine grasslands only.



In the calculation of the moisture stress in the climate scenarios use is made of repro-functions, calculated with the SWAP model, that may be less accurate in extreme climatic situations (see Section 5.3). As a check, in the Smalbroeken area direct calculations of the moisture stress were made with the SWAP model, using the precipitation and evaporation from the climatic data, the groundwater levels and the hydraulic head from SIMGRO simulations. Calculations were made for 12 points in a sequence trough the river valley. The outcome was in line with the results mentioned above. Although evaporation is much larger in the *EhsBuf_HadPi* scenario than in the present situation, moisture supply is still sufficient and except for extreme years moisture tension in the wettest parts never falls under a critical level of -12 m.

Table 9.5 Increase (in ha) of wet and very moist sites with moisture stress in the most dynamic scenario *EhsBuf_HadPi* (wetter in winter and spring due to increased rainfall, dryer in summer due to increased evaporation) compared to the present-climate scenario *EhsBuf_His*.

	EhsBuf_His			***EhsBuf_HadPi***		
	moisture stress			moisture stress		
	none	little	moderate	none	little	moderate
wet riverine grasslands	104	-	-	144	-	-
very moist riverine grasslands	174	-	-	212	-	-
wet heathland	112	1	-	152	4	-
very moist heathland	189	5	0	247	12	4

9.2.5 Conclusions

The effect of climatic changes on the occurrence of wet and very moist riverine grasslands is likely to be small, and in most scenarios positive: in the driest scenario (*EhsBuf_Had*) no change, in the wettest scenario (*EhsBuf_HadPiEr*) an increase with 42% is predicted. Further more, the expected climate changes do not lead to moisture stress in the wet and very moist riverine grasslands. This is connected to the fact that these ecosystems mainly occur in upward seepage areas, which are well buffered against changes in hydrology. Changes in watertable are relatively small, and shortages in moisture supply are not likely to occur as a result of upward seepage. In contrast, in the upland infiltration areas much larger changes in the area of wet and dry heath can be expected, which is linked to the fact that changes in watertables are much larger there.

However, a reservation must be made in regard to the conclusions that wet mesotrophic riverine grasslands are not threatened by the predicted climatic change. In this study no attention was given to the possible effects of increased flooding (Figure 7.1). In itself flooding is no threat for the vegetations that are characteristic for wet and very moist riverine grasslands, or may even have beneficial effects. However, the water of the Beerze and Reusel rivers is very eutrophic. Without changes in water quality increased flooding with river water will undoubtedly result in eutrophication. This might lead to a decrease in wet mesotrophic grasslands, and an increase in species-poor sites of high nutrient availability dominated by *Glyceria fluitans* and other less valued species.

10 TEMPERATURE EFFECTS ON AQUATIC AND TERRESTRIAL ECOLOGY

10.1 Temperature and macro-invertebrates

P.F.M. Verdonschot & Tj.H. van den Hoek

10.1.1 Introduction

Temperature changes will directly and indirectly affect macro-invertebrates inhabiting lowland streams in the Netherlands. The temperature in natural streams is determined by a number of interrelated key factors (Ward 1985). The key factors acting in natural lowland streams are included in Figure 10.1.

The stream temperature characteristics determined by hydrology depend on the location in the tributary system (upper-, middle-, or lower-course) and the relative contributions of surface runoff and groundwater. Spring-fed streams receive a proportionately large inflow of groundwater, which has a constant temperature and thus causes these streams to be thermally very constant. Insolation is also an important key factor for stream temperature regime, but that will not change through climate change.

Figure 10.1 Key factors determining the temperature regime of a natural lowland stream (altered after Ward 1985).

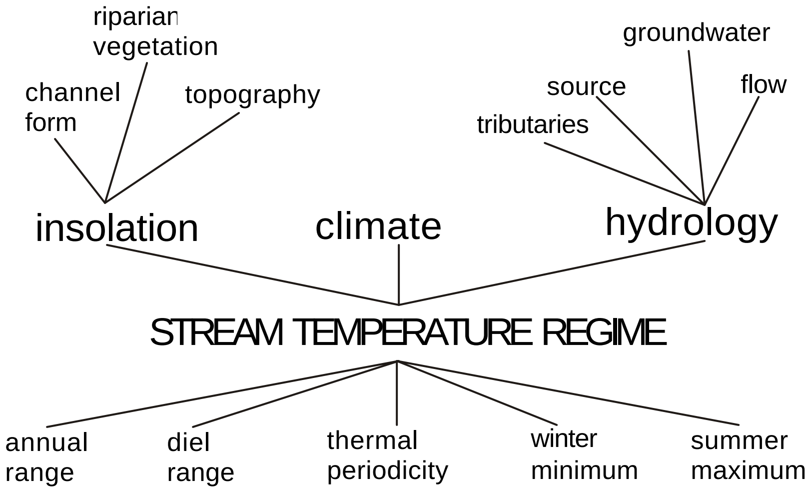
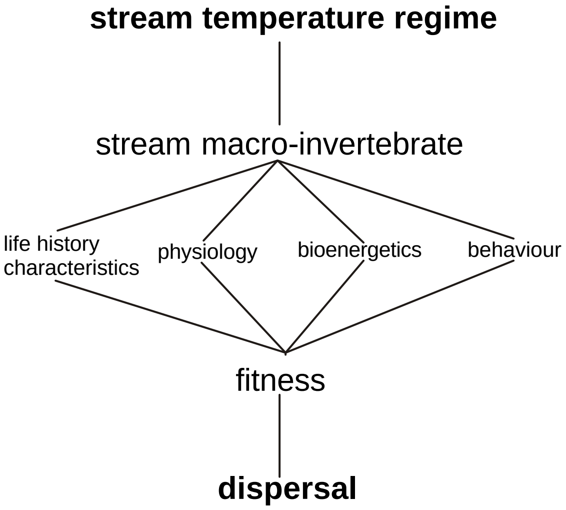


Figure 10.2 Conceptualization of the effect of stream temperature on the dispersal of macro-invertebrates.



The effect on a stream of the increasing level of atmospheric CO_2 acts through the chemical quality of the leaf litter entering the stream. Leaf litter produced under conditions of elevated CO_2 have both higher C:N ratios and lignin content. Therefore, leaf litter that falls into the stream will be decomposed more slowly because of decreased microbial colonization. This in its turn causes a reduction in detritivore and filter-feeding macro-invertebrate abundance (Wahtera et al. 2000).

In stream ecosystems, it has long been realized that temperature plays an important role in determining the distribution and abundance of macro-invertebrates (e.g. Kamler 1965, Vannote & Sweeney 1980, Ward & Stanford 1982). Temperature is one of the most important factors affecting the life history characteristics and biogeography of aquatic insects (Sweeney 1984). Macro-invertebrates are poikilothermic (cold-blooded) animals whose metabolism, rate and magnitude of growth, development, and overall behavioral activities respond significantly to thermal change on a diel, seasonal, and annual basis (Ward & Stanford 1982). As macro-invertebrates are found in a wide range of waters with different thermal regimes, they clearly possess bioenergetic, physiological, developmental, and/or behavioral mechanisms that enable them to survive, reproduce (Sweeney et al. 1992) and disperse (Figure 10.2).

The major goal of this part of the study is to reach a better understanding of the potential effects on macro-invertebrates in lowland streams that occur if climate changes towards a warmer atlantic regime. That regime presently occurs in the northern half of France. The study comprises two parts. The first part focuses on the expected temperature change and answers the question: ‘What temperature change is to be expected in lowland streams in the Netherlands?’. The second part focuses on the question: ‘Which macro-invertebrate species will decrease or disappear, will not change, or will increase or colonize the lowland streams in the Netherlands due to climate change?’.

10.1.2 Methods

Temperature regimes

Five of the ten streams described in Chapter 6 were intensively monitored for temperature from July 1997 until October 1998, over a 15-month period. Temperature was recorded each 15 minutes. Measurements were expressed in daily and monthly averages. Based on one year, the temperature of the studied streams was summarized in percentiles of twenty-five percent each. The temperature values of these classes, expressed in ^{o}C, represent temperature quartiles.

Two climate scenarios are used to predict the future temperature regime, the so-called RIVM scenario (Können, Fransen & Mureau 1997) and the Hadley scenario *Cur_Had* described in Section 2. The air temperatures predicted in both scenarios are used to calculate the water temperatures. To do so, linear regression is used to relate the measured daily average water temperature to the measured daily air temperature per stream. The resulting regression coefficients are used to calculate the future water temperature on the basis of the future air temperature.

Macro-invertebrates were sampled 3 times in all ten streams in autumn (1997), spring (1998) and autumn (1998). The samples were taken by means of a micro-macrofaunashovel of 10 by 15 cm (sampled surface area 150 cm^2). At each site the five major substrate types were sampled, sorted and preserved in alcohol (70% dilution), except for oligochaetes and watermites which were preserved in formalin (4% dilution) and Koenike fluid, respectively. If possible, all macro-invertebrates were identified down to the species level. Macro-invertebrate distribution is related to the stream temperature regimes. Number of taxa, number of individuals and some ecological characteristics of macro-invertebrates are calculated (Verdonschot 1990, Nijboer & Verdonschot 2001).

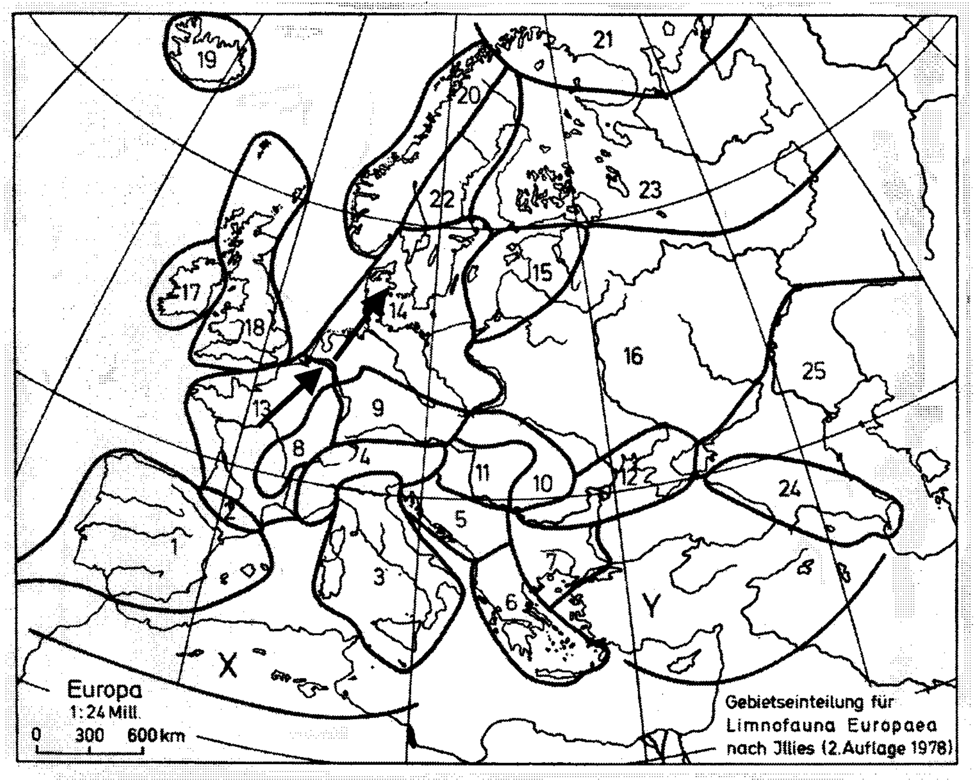
Dispersal

To study the present and expected dispersal patterns of macro-invertebrates the biogeographic information listed by Illies (1978) is used. The criteria to select suitable macro-invertebrate species are:

- the species must occur in lowland streams
- the species must be present in the atlantic region of the north-western European lowland plain

The latter criterion implies that only species occurring in ecoregion 13 and 14 (Figure 10.3) will be used. The first criterion is met by selecting only running water species. Ecoregion 13 ‘Western European lowland plain’ covers the western parts of France and Belgium up to the southern part of the Netherlands, south of the river Rhine. Ecoregion 14 ‘Central European lowland plain’ covers the Netherlands, north of the river Rhine, northern Germany, Denmark and southern Scandinavia. Macro-invertebrates currently occurring in ecoregion 13 concern the species to be expected in the Netherlands in the future. The dispersion of macro-invertebrates currently occurring in ecoregion 14 will shift towards the north. A number of

Figure 10.3 Ecoregions in Europe (Illies 1978). The arrows indicate the expected direction of change in macro-invertebrate distribution.



species will disappear from the Netherlands. Three classes of biogeographical change are defined:

- class I : extinction, in which a taxon occurs in ecoregion 14 and lacks in ecoregion 13
- class II , introduction, in which a taxon lacks in ecoregion 14 and occurs in ecoregion 13
- class III, constant, in which a taxon occurs in both ecoregions

The number of species are scored for each macro-invertebrate group.

10.1.3 Temperature regimes

The temperature regimes of the five studied streams show two temperature groups of streams (Figure 10.4). The first group, Springendalse stream north, Cold stream and Old stream, show minor fluctuations daily as well as over the seasons. The daily averages fluctuate from 3.4 ^{o}C up to 13.3 ^{o}C. These values indicate streams which are fed by deep ground water (left-hand side of Figure 10.5). This groundwater has a constant temperature and together with the small size of the streams, stream temperature does not vary much throughout the year. Figure 10.5 also shows that in future temperature will especially rise in winter by about 2 ^{o}C.

Two other streams, Tongerense stream and Forest stream, show larger fluctuations in time (right-hand side of Figure 10.5). The daily averages fluctuate from -0.2 ^{o}C up to 19.4 ^{o}C. Both streams are fed by rainwater or shallow subsurface runoff. Furthermore, both streams are slow flowing. Flow velocity together with water source cause this temperature regime. Figure 10.5 also shows that in future temperature will rise throughout the year by about 4^{o}C. The same pattern is visible in all five streams comparing daily minimum and maximum values.

Figure 10.4 The average daily temperature in five lowland streams.

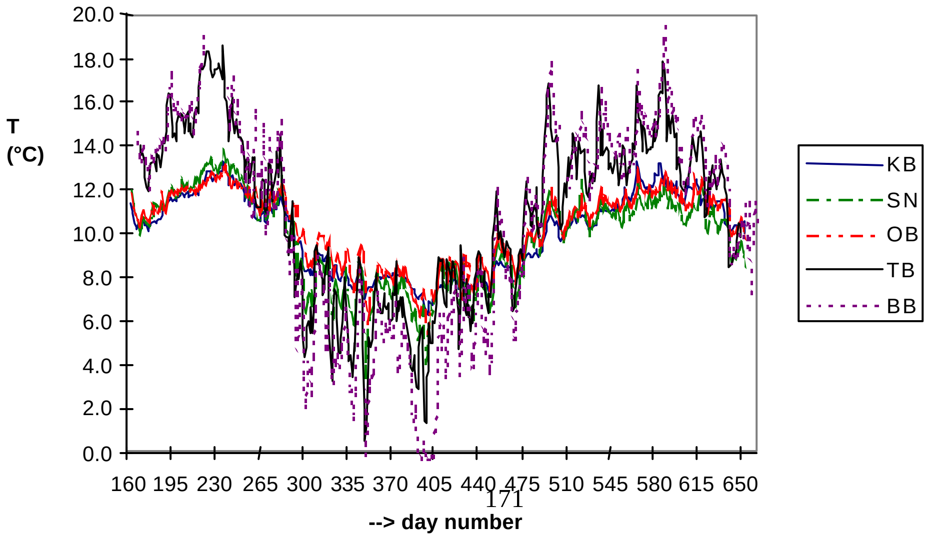
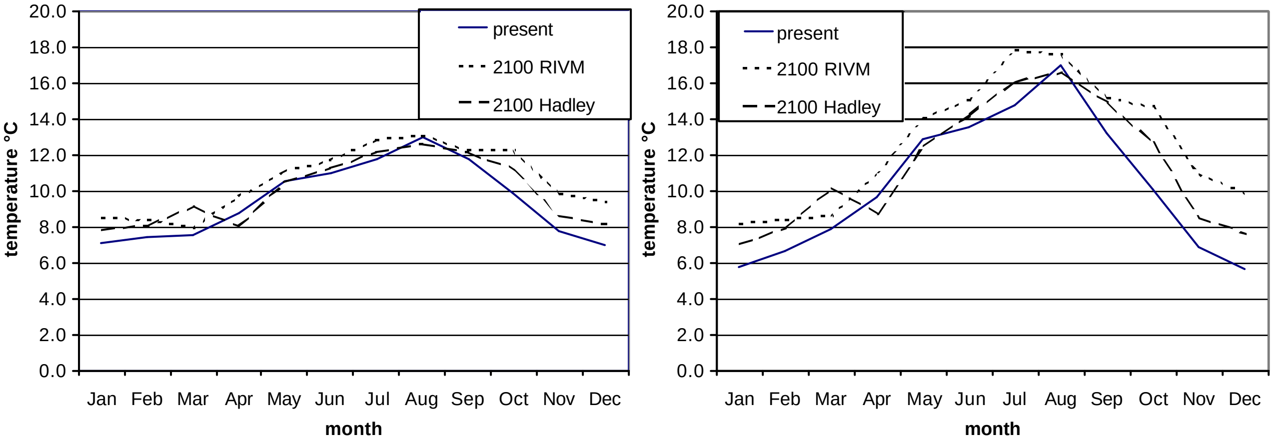


Figure 10.5 Present and predicted temperature regime in groundwater fed (left: Springendalse stream north) and a rainwater fed lowland stream (right: Tongerense stream).



The macro-invertebrate composition of both groundwater fed and rainwater fed streams is compared (Table 10.1). This comparison is based on two major criteria:

1. Species with a narrow temperature range will, because cold waters are rare in the Netherlands, be rare
2. Species with a narrow temperature range, especially, will occur in springs and small upper courses of streams

The relative number of rare species and species characteristic for springs and small upper courses is much higher in groundwater fed streams (Table 10.1). This result supports the hypothesis that a number of running water macro-invertebrates, often more common in alpine areas, can occur in the lowlands because of the constant supply of those streams with cold groundwater. It also implies that these species are vulnerable to climate change, especially, when higher air temperatures in the long term also affect the groundwater temperature.

Table 10.1 Macro-invertebrate distribution in groundwater and rainwater fed lowland streams.

stream type	no. taxa (no. unique taxa)	no. of individuals	no. rare taxa	no. spring taxa	no. upper course taxa
Groundwater fed	504 (unique 31 (7.4%))	9923	19 (61%)	6 (32%)	11 (58%)
Rainwater fed	699 (unique 52(6.2%))	9423	23 (44%)	3 (13%)	9 (39%)

10.1.4 Dispersal

It is clear that climate change will influence the life history characteristics and biogeography of aquatic macro-invertebrates. Changes in temperature regime will affect the fitness of individual species in terms of survival/mortality, growth/fecundity and production of viable offspring. If macro-invertebrates are unable to endure changing conditions, the only option to avoid extinction is dispersal to a location with a more suitable climate. Thus species can become extinct (class I), they can show no changes (class III) or they can newly colonize an area (class II). Figure 10.6 illustrates an overall change in macro-invertebrates composition in lowland streams to be expected under influence of climate change.

The numbers of taxa are listed per macro-invertebrate group in Figure 10.7. Climate change will cause a disappearance of species belonging to the groups of Oligochaeta (44%) and Orthocladiinae (31%). The change in the oligochaete fauna can be due to the lack of knowledge on the dispersal of oligochaete taxa when compiling the ‘Limnofauna Europea’ (Illies 1978). The extinction of a number of Orthocladiinae with a temperature increase is less surprising. This sub-family of the Chironomidae mainly inhabits cold waters, thus this group is relatively over-represented in small lowland streams. Other groups characteristic for this environment, e.g. the Plecoptera, do not show a strong decrease in number of species. This could be due to the fact that most of these species are already extinct from the Netherlands.

Figure 10.6 Number of species per biogeographical class of change per macro-invertebrate group.

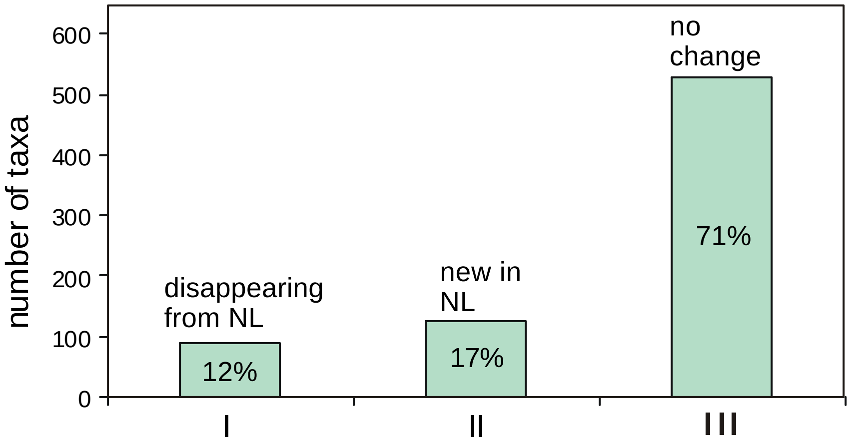
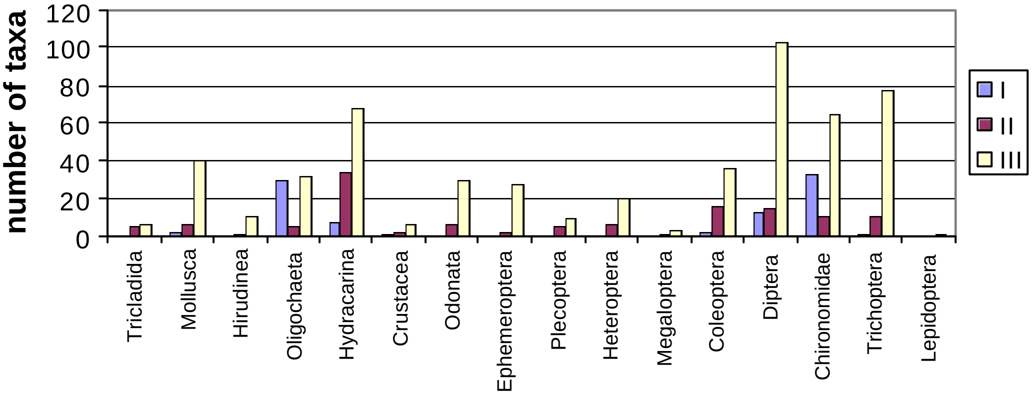


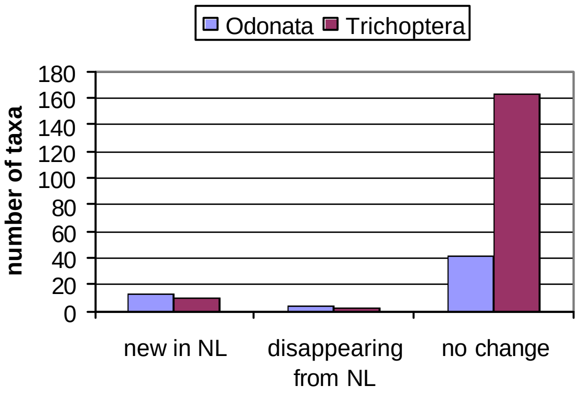
Figure 10.7 Percentage change of macro-invertebrate species in the Netherlands due to climate change (expressed in class I or III as explained in the text).



On the other hand new species will colonize our lowland streams. The percentage of new species within a group is highest for the Tricladida (46%), high for the Plecoptera (36%), Hydracarina (31%) and Coleoptera (30%), and reasonable for the Heteroptera (23%) and Odonata (17%). The relatively high percentages for Tricladida and Plecoptera are somewhat flattered because of the low numbers of species. Most of the macro-invertebrates show no change, with the most constant groups being the Ephemeroptera (93%) and the Hirudinea (91%). This only means change in the qualitative sense of colonizing or becoming extinct. The increase or decrease of populations will surely occur and probably even affect the function of the stream ecosystem considerably. But this impact is difficult to predict because of the lack of knowledge on population dynamics and life history characteristics of the species. Furthermore, the present often-deteriorated state of many Dutch streams is not included.

The method used is based on the dispersal data in the ‘Limnofauna Europea’ from 1978. More recently, for at least two macro-invertebrate groups more accurate updates of dispersal data became available. These groups concern the Odonata (Bos & Wasscher 1997) and the Trichoptera (Tobias & Tobias 1981). The criteria used were defined stricter by refining ecoregion 13 and to consider only those species within this region which already occur up to about 600-700 km south of the Netherlands. The same distance measure was used for the species to become extinct because of a shift towards the North. Species already extinct from the Netherlands and species which are only observed as adults are taken apart. Furthermore,

Figure 10.8 Percentage of change of Odonata and Trichoptera species in the Netherlands due to climate change.



the selection in this analysis included all species and was not restricted to only the running water representatives.

The percentages of species colonizing or disappearing from the Netherlands are listed (Figure 10.8). Thirteen new odonates (ten of which are running water species) and ten new trichopterans are to be expected while seven (four running water species) respectively two (both running water species) will become extinct. Both groups will take advantage from climate change, their number of species will increase. This more detailed analysis shows some differences with the Illies data and indicates how careful these first results should be handled.

10.1.5 Conclusions

Lowland streams in the Netherlands can be fed by mainly groundwater or mainly rainwater. The relative shares of both determine the temperature regime of a stream. A clear difference in macro-invertebrate composition, especially in rare species and species indicative for springs and small upper courses, is seen between mainly-groundwater and mainly-rainwater fed lowland streams. Climate change will affect the macro-invertebrate composition of springs and upper courses in the Netherlands.

If climate changes to a temperature regime comparable to that of the northern part of France and macro-invertebrates are able to disperse, especially the groups of Tricladida, Hydracarina, Plecoptera, Odonata, Coleoptera and Heteroptera will profit. Their number of species will increase in the Netherlands. The numbers of Orthocladiinae and Oligochaeta will decrease. The first corresponds with literature data (Rossaro 1991, Oswood 1989, Beckett 1992, Milner

1994). The conclusion on the oligochaetes is not supported, and probably due to lack of biogeographical knowledge. The more precise approach for odonates resulted in a higher number of expected species. The same approach for trichopterans also showed some inconsistencies in the 'Limnofauna Europea' already noted.

10.2 Temperature effects on terrestrial ecology

A.H. Prins & J. Runhaar

10.2.1 Introduction

To obtain an impression of direct temperature effects on the species composition of wet and moist riverine grasslands it was decided to use a reference area. In this area geological and hydrological conditions should be more or less comparable to those in the Dutch lowland pleistocene areas (brook valleys with wet grasslands in a region with predominantly non-calcareous sands) and the climate should resemble the conditions predicted for the Netherlands in the next century.

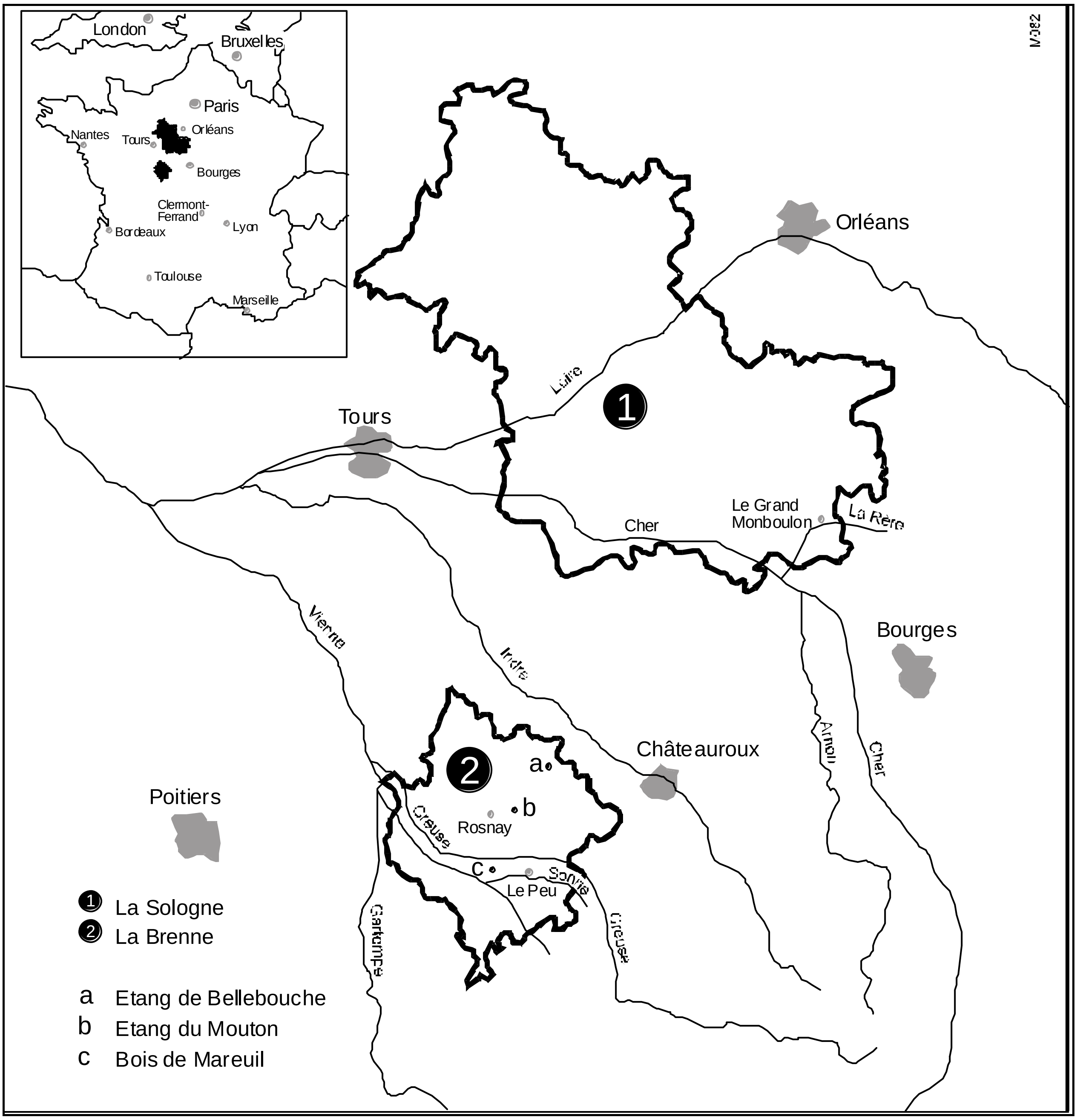
For the period 2070-2100, that has been chosen as a reference period in the present study, an increase in temperature of 2.8°C is predicted (Section 2.2). From comparison with data in the database given by Van der Voet *et al*. (1996), it appears that the Hadley climate scenario is reasonably well approximated by conditions in North-central France. For instance, a location with 2.25^{o} Eastern Longitude and 46.75^{o} Northern Latitude has a mean annual temperature of 11.9 ^{o}C and a mean annual precipitation of 710 mm/yr, as compared to the Hadley values of respectively 12.6 ^{o}C and 777 mm/yr. It was therefore decided to choose central France as a reference area in the study on the direct effects of climate change.

10.2.2 Description of the reference area

Two regions in central France were chosen as a reference to study the direct effect of climate change on wet and dry grasslands: La Sologne and La Brenne (Figure 10.9). These regions are situated on the border of the high Massif Central and the low-lying basin of Paris. The area can be characterized as a lowland area with brook valley systems and non-calcareous sandy soils. In this respect, the area is comparable with the Beerze and Reusel drainage basin.

La Sologne is situated to the south of Paris. The soil consists of Pleistocene sand that to a large extent is derived from the Massif Central. It is mentioned as a 'zone atlantique faiblement podzolique' (Allorge & Gaume 1931). Clay deposits in the sand form impermeable layers. Therefore, especially in the central part of La Sologne, many lakes are found. In the

Figure 10.9 La Sologne and La Brenne in France



twelfth and thirteenth century, this area of France was very prosperous with large vineyards, meadows and pastures. As a result of several wars and the plague, the area deteriorated, as large parts of France and Europe did in the Middle Ages. La Sologne became abandoned and desolated during that time. Heathland and woodland covered most of the area. Presently, the area is very popular to people from Paris. Much land is owned by them, and made into hunting ground. This process is called 'solognification' in France.

La Brenne is situated west of Châteauroux. It is divided in a northern and southern part by the river Creuse. The area has the status of a 'parc naturel régional'. It consists of 166.000 ha. It is famous because of the more than one thousand lakes (*étangs*) and the small hills (*boutons*). The lakes are artificial. The people of La Brenne made them by damming the lower lying places, that used to be the wettest sites. In the Middle Ages monks, who created the lakes to keep fish in, initiated this habit. The impermeability of the soil is caused by clay layers, comparable to that found in La Sologne. The making of lakes is still going on. Some decades ago ca. one thousand lakes were counted in the area, while currently about twelve hundred lakes are present. The small hills (*boutons*) consist of sandstone. Their mean height is about five meters, the diameter is between ten and thirty meters. A dry vegetation (heathland or woodland) is found on these small hills. The *boutons* are a characteristic element in the landscape. The area used to be in agricultural use. Mixed farms were most commonly found. During the last two decades, a lot of farms have been abandoned. Like La Sologne, the soil in La Brenne consists of pleistocene sand. Clay layers are found in the soil in most of La Brenne. The deeper soil consists of chalk, that was formed during the Cretaceous period (Ledoux 1995).

The climate in La Sologne and La Brenne is Atlantic. The summer period is very dry. From the second half of June till September or October there is hardly any rainfall. In autumn, however, a lot of rain may fall. Because of the clay layers that are found in a large part of La Brenne, the soil may be very wet until June. When the dry period starts, the watertable falls sharply. The watertable is therefore fairly variable.

In the reference areas La Sologne and La Brenne, five transects were described in the period 27 June to 30 June 1998. On each of these transects, three to seven vegetation relevés were made. The relief, hydrology and abiotic conditions (soil texture, pH) were recorded on the relevé sites. Table 10.2 gives a list of the study sites and the type of vegetations found.

Table 10.2 Studied sites in the reference area in France and the vegetation types that were examined.

Area	Location	Vegetation types
La Sologne	La Rère	Filipendulion Alno-Padion
La Brenne	La Carrière	Calthion
	Etang de Mouton	Caricetum elatae Junco-Molinion Calluno-genistion Plantagini-Festucion
	La Sonne	Calthion Filipendulion
	Bois de Mareuil	Caricion gracilis Calthion
	Etang de Bellebouche	Caricetum elatae Hydrocotylo-Baldellion Junco-Molinion Nardo-Galion

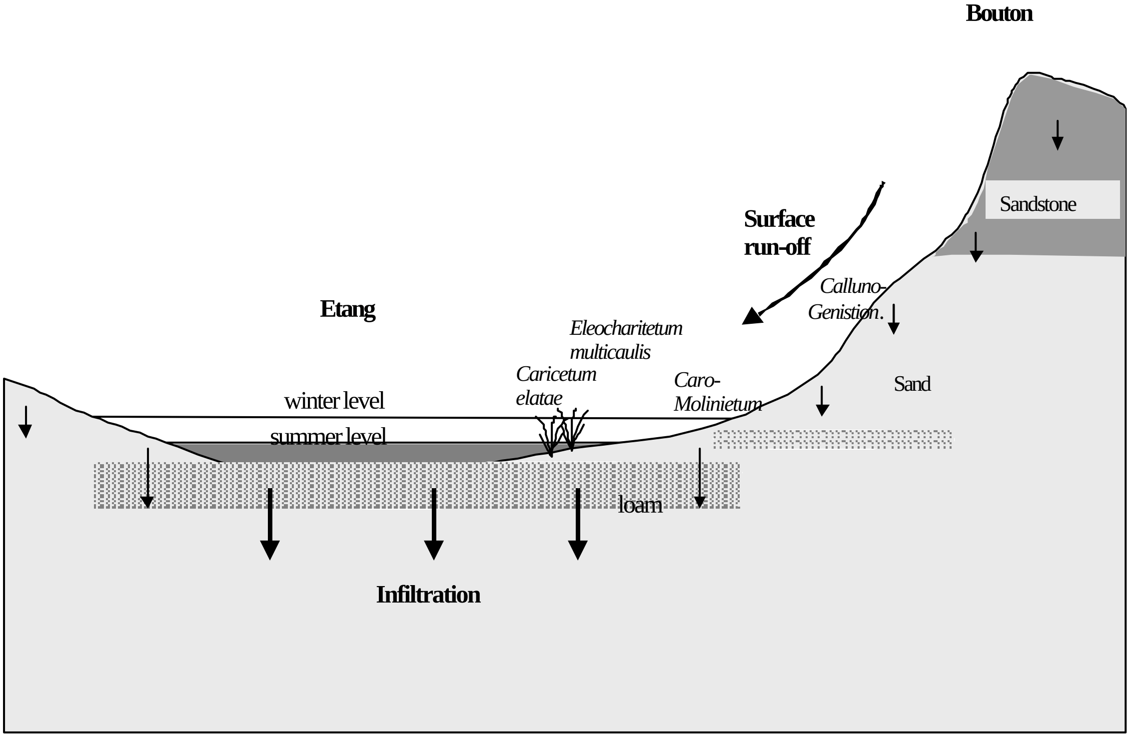
10.2.3 Description of wet grasslands in the reference areas

Species-rich grasslands on wet and moist soils with a low availability of nutrients, as described for the Beerze-Reusel study area in the Netherlands (*Junco-Molinion*), are only marginally found in La Brenne. The abiotic characteristics of the French reference site differ from those in the Netherlands. In the Beerze-Reusel area the *Junco-Molinion* grasslands belonging to the *Cirsio-Molinietum* are found in seepage areas. These grasslands are dependent on groundwater. French *Junco-Molinion* vegetations belonging to the related *Caro verticillati-Molinietum* (Nomenclature according to De Foucault 1984) are found on hydromorphic soils with pseudogley, i.e. on soils in which percolating rainwater stagnates during part of the year.

Figure 10.10 gives a generalized description of the gradient in which the *Caro-Molinietum* vegetations were found in La Brenne along the Etang de Bellebouche and Etang de Mouton. They occur in a narrow zone that is flooded in winter. In the summer the water level drops quickly, from (far) above the surface level to 1 or 1.5 m below surface level. Because of

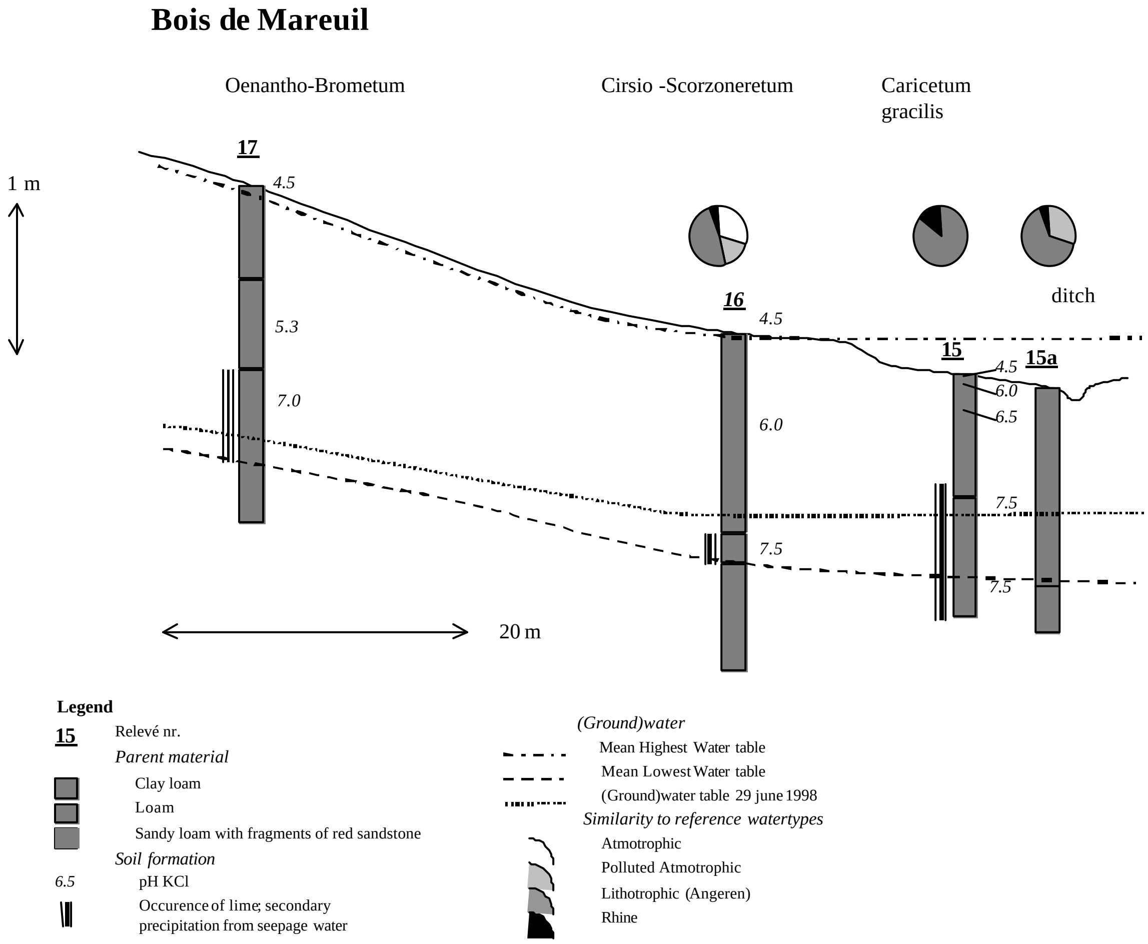
Figure 10.10 Position of *Caro-Molinietum* vegetations as found at the Etang de Bellebouche and Etang de Mouton locations. The 'boutons' form the remnants of a sandstone carapace that once covered the plateau. In the lower parts loam deposits occur on which water stagnates. The *Caro-Molinietum* vegetations occur on the places that are flooded in winter only.

the high impact of rain water, that accumulates during winter lasting until the end of spring, the *Junco-Molinion* grasslands are characterized by a low pH. Compared to the Dutch sites, the higher presence of the heathland species *Calluna vulgaris*, *Erica tetralix*, *Erica scoparia*, *Ulex minor* and *Genista anglica* is significant. Species that differentiate the *Caro verticillati-Molinietum* from the *Cirsio dissecti-Molinietum* are *Lobelia urens* and *Carum verticillatum*.



The Dutch nutrient rich wet grasslands of the *Calthion palustris*-type are most similar to the French meadows with *Oenantho peucedanifoliae-Brometum racemosi* vegetations (de Foucault 1984), and to a lesser extent with the *Cirsio dissecti-Scorzoneretum humilis,* that is intermediate between *Junco-Molinion* and *Calthion vegetations*. Meadows with these types of

Figure 10.11 Transect in the Bois de Mareuil location.



vegetation are found on hydromorphic soils with gley. The upper horizon of the soil is mineral or slightly organic. In La Brenne area they are best represented in depressions and brook valleys in the southern part (La Sonne, Bois de Mareuil). Figure 10.11 gives a description of one of the transects with these types of vegetation. The *Oenantho-Brometum vegetations* are floristically rather similar to the Dutch *Senecio-Brometum* vegetations. Species specific for the *Oenantho-Brometum* vegetations are *Oenanthe peucedanifolia, Bromus racemosus, Juncus acutiflorus, Lotus uliginosus* and *Alopecurus pratenis*.

In La Sologne and La Brenne we did not record a situation that can be floristically compared with the Dutch *Caricion nigrae*.

10.2.4 Discussion

Despite the large distance and the differences in geography and climate, the floristic composition of wet mesotrophic grasslands in the reference area is often very similar to that in the Netherlands. Wet, nutrient-poor grasslands belonging to the *Caro-Molinietum* are relatively species-poor compared to the most related *Cirsio-Molinietum* vegetations in the Netherlands. However, this is probably due to the fact that in La Brenne they occur in sites that are rather unfavorable compared to the Dutch situation. In the Netherlands *Cirsio-Molinietum* vegetations occur in stable upward seepage areas whereas in the Brenne Caro-Molinietum vegetations occur only marginally in infiltration areas, in places that are inundated in winter and that are much more dynamic and more acid.

Wet nutrient-rich grasslands are more comparable in terms of abiotic conditions. The *Senecio-Brometum* associations in the Netherlands and the *Oenantho-Brometum* in La Brenne both occur on wet base-rich gley soils, often in places with upward seepage. Comparing the species composition of the Dutch and French nutrient-rich wet grasslands, the frequent occurrence of umbelliferous plant species in the French situation is striking. *Oenanthe silaifolia*, *Oenanthe peucedanifolia*, *Silaum silaus* and *Carum verticillatum* are frequently found in the French sites, often as dominating species. Most umbelliferous plant species have a taproot and make no stolons (Weeda et al. 1987). This may explain their abundance in the vegetation types that have been studied in the reference area in France. These sites have summer groundwater levels that are relatively low in summer, which is more favorable for deep-rooting species.
The umbelliferous species mentioned all have a more atlantic distribution range and are absent or rare in the Netherlands, although some of them were more common in the past (Weeda et al. 1987; Cools 1989; van der Meijden 1996). The species may possibly become accustomed in the Netherlands when there is a lasting temperature increase as a result of climatic change, on the understanding that stand conditions are favorable. This is also found for *Scorzonera humilis.* Four species are presently not found in the Netherlands: *Gaudinia fragilis, Orchis laxiflora*, *Galium debile* and *Lobelia urens.* They may invade the Netherlands when temperature will rise for 2 or 3°C for a longer lasting period.

A remarkable difference is that in the reference area no *Caricion nigrae* vegetations were found. In the Netherlands, the grasslands of the *Caricion nigrae* type often occur on the borders of brook valleys, often in places were rainwater lenses are formed that cause a superficial acidification of the site. In the study area in La Sologne and La Brenne we did not record situations that are floristically or hydrologically similar to the dutch *Caricion nigrae* sites. The most likely explanation is that evaporation deficits in summer are too large to permit the presence of permanent wet places with rainwater lenses. The relatively low summer groundwater levels are probably also the cause for the absence of peat in the reference situation: the combination of good aeration and high temperatures stimulates the oxidation of organic matter. In general peatland ecosystems in France are rare and have a scattered distribution pattern (Goodwillie 1980).

In permanently wet mesotrophic places with accumulation of organic matter sedges (*Carex spec.*) often form the predominant life form. The fact that many sedges have a more northern geographic distribution or are rare in France may be caused by this dependency on permanent wet sites. In La Brenne the number of *Carex* species is limited, with *C. elata* that occurs along the fringes of the Etangs as most common species. Species such as *C. elongata, C. pseudocyperus, C. nigra and C. remota,* that are common in the Netherlands, are absent.

It is not certain how long it will take more southern species to invade the Dutch brook valleys. To invade areas outside the present distribution area seed or plant parts have to disperse. Abiotic vectors for dispersal (wind, water) are particularly associated with open and impermanent habitats. In more stable habitats (e.g. woodland), dispersal by animals may become more important (Hodgson & Grime 1989). Usually, wind dispersal is not far-reaching. Dispersal distances of less than 10 m are found for chalk grassland species (Verkaar et al. 1983) as well as for Asteraceae (Sheldon & Burrows 1973). Patterns of seed rain follow a bell-shaped curve, with a small proportion dispersing over long distances and the majority falling close to the parent (Harper 1977, Strykstra & Bekker 1997, Strykstra et al. 1996). Sometimes long-distance transport is achieved by water or wind-dispersal (Nip-Van der Voort et al. 1979, Marshall & Hopkins 1989). However, some authors think that long-distance dispersal is often overemphasized, based on rare accidental dispersal (Stieperaere & Timmermans 1983).

With regard to the Umbelliferous species that are characteristic for the French situations the conditions for dispersal may be favorable. Some of them already occur in the southern parts of the Netherlands or in nearby border areas, and seeds may easily be distributed with river water. *Oenanthe silaifoila,* that is a common species in the reference area, was considered to be extinct in the Netherlands since 1899. Recently, one individual of *Oenanthe silaifolia* has been found in the Netherlands (Schaminée 1999). It is expected to have been dispersed over a long distance by the water of the river Maas. However, for some of the other, more southern species dispersion will be more difficult since the large agricultural and industrial areas north of Paris and in Belgium form barriers for dispersion.

Species that reach the southern border of their distribution area in the Netherlands and that are characteristic for permanent wet, often slightly acidic sites with rain water lenses, such as *Potentilla palustris*, *Eriophorum angustifolium*, *Myrica gale* and many *Carex* species are likely to disappear in the situation of a lasting increase in temperature because of higher temperatures and because of the disappearance of suited habitats.

11 CONCLUSIONS AND RECOMMENDATIONS

11.1 Regional hydrology and stream morphology

It appears that the peak discharges of streams are highly sensitive to precipitation. In scenario *Cur_HadPi* with a 17% increased winter precipitation both of the investigated streams Beerze and Reusel reacted with peak discharges that are >50% higher than in the current situation. So the increase of winter precipitation is amplified by a factor three in the peak discharges. But when the statistics of the precipitation series are taken into account, the effect is less dramatic: the 10-day moving average of the precipitation – that is known to determine the peak discharges after a build-up of watertables – increases by 25% instead of the 17% increase of the mean winter precipitation. So the effect on the peak discharge is double that of the relevant precipitation parameter, and not treble as suggested when just looking at the precipitation means. The underlying cause of this ‘doubled’ reaction to increased winter precipitation is the increase of very wet areas along the stream-valley bottoms: the percentage area with a Mean Highest Watertable above 25 cm below soil surface increases from 4.6% to 7.3%. That is a 59% increase, corresponding closely to the percentage increase of peak discharges. For watertables higher than 25 cm b.s.s. (below soil surface) the trenches/furrows with low drainage resistance are activated. In the SIMGRO-model this class of drainage media is used for modelling the influence of the soil surface: low-lying parts of the soil surface start to act as drainage media when the surface becomes inundated. At full inundation the drainage resistance is reduced to 1 d (Figure 3.5).

In scenarios *Cur_HadEr* and *Cur_HadPiEr* the possible effects of reduced evapotranspiration were investigated. This reduction of crop evapotranspiration will possibly take place as a consequence of increased CO_2-content in the atmosphere. The possible reduction of evapotranspiration investigated in scenarios *Cur_HadEr* and *Cur_HadPiEr* reduces the lowering of watertables at the end of summer, meaning that the build-up of high watertables during the winter period has a ‘wetter’ starting point. The reduced evapotranspiration adds an additional 7% to the computed peak discharges.

The investigated land and water use scenarios do not appear to have much influence on the peak discharges. Even the free meandering of streams with a shallowing of the stream cross-section does not seem to have much effect. That the expected increase of peak discharges does not occur is due to the compensating effect of the increased sinuosity of the stream: the lengthening of the stream in the meanders reduces the water level gradient. That makes the stream more sluggish, and the stream itself becomes more of a bottleneck in the discharge process. So it seems that nature development measures do not necessarily lead to a reinforcement of effects caused by increased precipitation of a climate scenario. That the bufferzones around the new nature of the National Ecological Network (scenarios *EhsBuf*) do not very much affect the discharges is because the investigated zones still involve a form of agriculture (extensively farmed grassland with no agricultural drainage and ditches not deeper than 90 cm). And, even more important, the upward seepage needed for extremely high watertables is not present there.

In the stream valleys the upward seepage to the root zone - essential for the terrestrial ecology - is sensitive to the climate change. In scenario *Cur_Had*, for instance, there is a 34% increase of the area with an upward seepage higher than the critical level of 0.5 mm/d. Here the evapotranspiration plays a most dominant role: every change of evapotranspiration leads directly to changes in the upward seepage to the root zone. That is because in the stream valleys the moisture supply is always optimal, so no reduction of evapotranspiration takes place. In scenarios *Cur_HadEr* and *Cur_HadPiEr* the increase of seepage predicted for scenarios *Cur_Had* and *Cur_HadPi* does not take place. That is because the actual evapotranspiration roughly equals the amount in the current situation: the reduced crop factors compensate for the increased potential evapotranspiration.

An increase of precipitation affects the upward seepage to the root zone much less than the evapotranspiration does. That is a consequence of two contradicting factors:

- increased precipitation raises water levels on the higher ridges between the valleys, where the infiltration areas are. This increases the water pressure in the subsoil, and therefore increases the upward seepage in the stream valleys
- increased precipitation also thickens the precipitation lense in winter, so it takes longer for the lense to vanish at the beginning of summer; this means that less seepage water can reach the root zone

It appears that the first factor slightly has the upper hand, so increased precipitation leads to slightly increased seepage to the rootzone.

The effects on the seepage to the root zone are attenuated in the case that free meandering of streams is allowed. In all scenarios the free meandering shallows the depth of the stream, and therefore less seepage is drawn directly into the stream, and more of it reaches the root zone. This system is of itself more robust and less sensitive for climate change: in scenario *EhsBufM_Had* compared to scenario *EhsBufM_His* there is a 20% change of area with seepage to the root zone higher than 0.5 mm/d.

For simulating the effects on the peak discharges the integration between groundwater and surface water was essential. For simulating effects on the upward seepage to the root zone, the integration between soil water and groundwater was essential. This stresses the point that effects of climate change can only be simulated with a regional model like SIMGRO that has a tight integration between all components of the regional hydrological system.

11.2 Aquatic ecology

To use macro-invertebrates as a group to indicate the effect of climate changes on the lowland stream ecosystems, a large field study was conducted. Ten streams were studied. Nine streams were classified by discharge parameters in different discharge dynamics classes. Furthermore, substrate patterns differed between all streams and showed more or less dynamic patterns. The streams were classified according to substrate and discharge dynamics hydro-morphological types. Discharge–substratum types appear not to be simple and predictable. As expected, flashy streams with a constant substrate pattern do not occur, and neither are there any constantly discharging streams with a dynamic substrate pattern. Streams can have a more constant discharge in time and still show intermediate substrate dynamics, as is shown by the stream with an intermediate discharge and a constant substrate pattern. Hydrology and substrates do not show simple linear relationships with macro-invertebrate distribution.

The macro-invertebrate distribution appeared to be explained by substrates at the habitat scale. Furthermore, these habitats seem to be strongly represented in at least one or a few of the studied streams. The analysis on the scale of streams included also a number of hydrological variables. The major distribution pattern is related to habitats but partly also explained by discharge dynamics parameters. At the scale of the stream a gradient from flashy streams (R_3 and R_4) towards constantly discharging streams (R_1) was shown. This gradient is partly affected by substrate and other environmental conditions.

In general, most indicative macro-invertebrates prefer specific substrates and stream velocity classes. These habitats of substrate and stream velocity occur under specific conditions which, within these ten streams, occur in one or a few streams. Many more data on different streams with different hydrological regimes are necessary to decide on a discharge-related preference for macro-invertebrates. Furthermore, discharge dynamics were the most important hydrological characteristic affecting macro-invertebrate distribution at the stream level. Therefore, discharge dynamics were translated in an ecological relevant measure; the discharge dynamics index (DDI). Four biological metrics were calculated for each of the studied streams and plotted against the discharge dynamics index (DDI). Trends between flow velocity, saprobity, rarity and diversity showed a clear and linear relationship with the DDI. Therefore, it was concluded that the biological metrics support the DDI as a measure of hydrological quality in the studied streams. The higher the DDI score is, the more natural a stream will become.

The DDI was calculated for sixteen different climate scenarios. The average discharge dynamics score differed for most of the scenarios significantly from the reference (current climate condition), even though the value of the average index only differed slightly. The scenarios all showed a decrease in the index score. Under all scenarios the climate change had a significantly negative effect on the stream community. When also looking at the sites which dry up for a longer period of time it appeared that all scenarios showed an extended number of desiccated sites. Desiccation is fatal for most stream communities.

Comparing the current climate condition with the implemented ecological infrastructure (*Ehs_..*), the EHS and buffer zone of extensive grassland (*EhsBuf_..*) and the EHS and buffer zone and free meandering main streams (*EhsBufM_..*), it is concluded that none of these additional measures significantly influenced the discharge dynamics index. This does not mean that especially the latter will not affect the macro-invertebrate community. On the contrary it will have a major effect but this parameter is not included in the hydrological quality assessment.

Lowland streams in the Netherlands can be fed by mainly groundwater or mainly rainwater. The relative share of both determine the temperature regime of a stream. A clear difference in macro-invertebrate composition, especially in rare species and species indicative for springs and small upper courses, is seen between mainly-groundwater and mainly-rainwater fed lowland streams. Climate change will affect the macro-invertebrate composition of springs and upper courses in the Netherlands.

If climate changes to a temperature regime of the northern part of France and macro-invertebrates are able to disperse, especially the groups of Tricladida, Hydracarina, Plecoptera, Odonata, Coleoptera and Heteroptera will profit. Their number of species will increase in the Netherlands. The numbers of Orthocladiinae and Oligochaeta will decrease.

11.3 Terrestrial ecology

With regard to wet riverine grasslands the effects of climatic changes are expected to be limited. Highest watertables and upward seepage in the river valleys hardly change or become better, so that the area of wet riverine grasslands is expected to remain the same or to increase, depending on the new balance between precipitation and evaporation. The effect of the positive influence (of climate change) on upward seepage on the vegetation is uncertain because the buffering of the soils also depends on other factors.

The main changes will be the increased evaporation and lower groundwater levels in summer, leading to more dynamic habitats. However, these changes are not so large that moisture stress is to expected to occur in wet ands moist riverine grasslands: even in the most dynamic scenario moisture supply to the vegetation is still sufficient.

In general hydrological changes in the river valleys are limited compared to those in surrounding infiltration areas. Compared with the large effects of human interference through drainage, canalization and cultivation effects of climatic changes are small. The largest change will probably be the disappearance of *Caricion nigrae* vegetations that depend on permanent wet sites with rainwater lenses and accumulation of organic matter. In general the conditions for the forming of peat will become unfavorable. In wet and moist grasslands with *Junco-Molinion* and *Calthion vegetations* floristic changes are expected to be limited. The most conspicuous effect will probably be the increase in umbelliferous species, some of which are already extending their distribution area to the North, and a decrease in abundance of species with a more northern distribution, including several *Carex* species.

With regard to these conclusions a reservation must be made for possible effects of increased flooding. In itself flooding is not a negative factor for wet and moist riverine grasslands, but present water quality in small rivers in the Netherlands is so poor that eutrophication is likely to occur. This might lead to the disappearance of the *Junco-Molinion* and *Calthion vegetations*. Because the factor flooding is not incorporated in our model, it is not possible to indicate to what extent eutrophication might occur.

In the study, attention was focused on the river valleys and the wet mesotrophic grasslands occurring there. However, the results of this study indicate that in infiltration areas groundwater levels and moisture supply react more strongly to changes in climatic conditions, and climatic changes may result in greater shifts in vegetation here. The most vulnerable are bog systems, which reach their southern distribution limit in the Netherlands and are likely to disappear with increasing evaporation.

In further studies on the effects of climatic change on small river systems it is therefore recommended to pay more attention to the effects of increased flooding and on the effects in infiltration areas.

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